Accelerator-based Neutrino Physics

Lecture 1

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References

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2. F.J.P. Soler, C.D. Froggatt, F. Muheim, “Neutrinos in Particle Physics, Astrophysics and Cosmology”, CRC Press, 2008.
3. C. Giunti and C.W. Kim, “Fundamentals of Neutrino Physics and Astrophysics”, Oxford University Press, 2007.
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6. R.N. Mohapatra, P.B. Pal, “Massive Neutrinos in Physics and Astrophysics”, World Scientific (2nd edition), 1998.
7. C. Sutton, “Spaceship Neutrino”, Cambridge University Press, 1992.
8. H.V. Klapdor-Kleingrothaus & K. Zuber, “Particle Astrophysics”, Institute of Physics Publishing, 1997.

Outline

Lecture 1: the past

1. How to make an accelerator-based neutrino beam
   - 1.1 Generic design of an accelerator-based neutrino beam
   - 1.2 Proton interactions on nuclear targets
   - 1.3 Magnetic focusing systems
2. History of accelerator-based neutrino experiments
   - 2.1 The two neutrino experiment
   - 2.2 Discovery of neutral currents
   - 2.3 Neutrino interaction experiments, nuclear structure, charm production
   - 2.4 Discovery of the tau neutrino

Outline

Lecture 2: the present

3. Accelerator-based neutrino oscillation experiments
   - 3.1 Short-baseline neutrino experiments: LSND, KARMEN, NOMAD, CHORUS, MiniBooNE
   - 3.2 Long-baseline neutrino experiments: K2K, MINOS, T2K, NOvA

Lecture 3: the future?

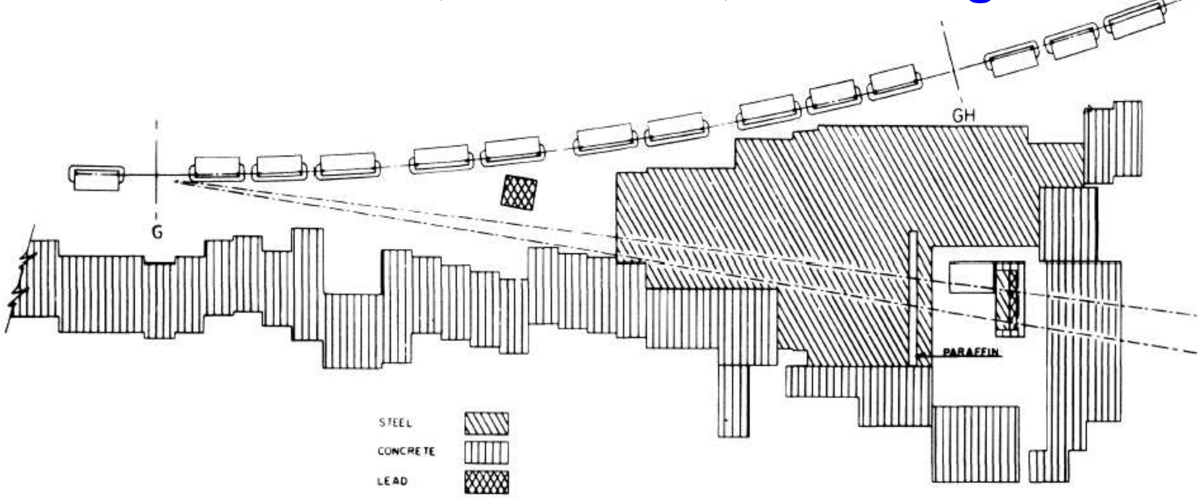
4. Future neutrino beams
   - 4.1 Remaining questions in neutrino oscillation physics
   - 4.2 Conventional accelerator-based Super-Beam experiments: CERN-Gran Sasso, T2HK, LBNE, LBNO
   - 4.3 Beta-beams: neutrinos from the decay of radioactive isotopes
   - 4.4 nuSTORM: neutrinos from a muon storage ring
   - 4.5 Neutrino Factory, the ultimate neutrino facility

1. How to make an accelerator-based neutrino beam

1.1 Generic design of an accelerator-based neutrino beam

First neutrino beams

- Excellent review article: **S.E. Kopp, arXiv:physics/0609129 Phys. Rept.439 (2007) 101.**
- First neutrino beam was created for the “two neutrino” experiment: **Schwartz, Lederman, Steinberger et al.PRL 9, 36 (1962)**



  - Protons of 15 GeV/c hit bare target at the AGS at Brookhaven
  - Production of pion and kaon secondaries
  - Pions, kaons decay: $\pi^{\pm} \to \mu\nu_{\mu}\ (\sim 100\%); K^{\pm} \to \mu\nu_{\mu}\ (63.4\%);$

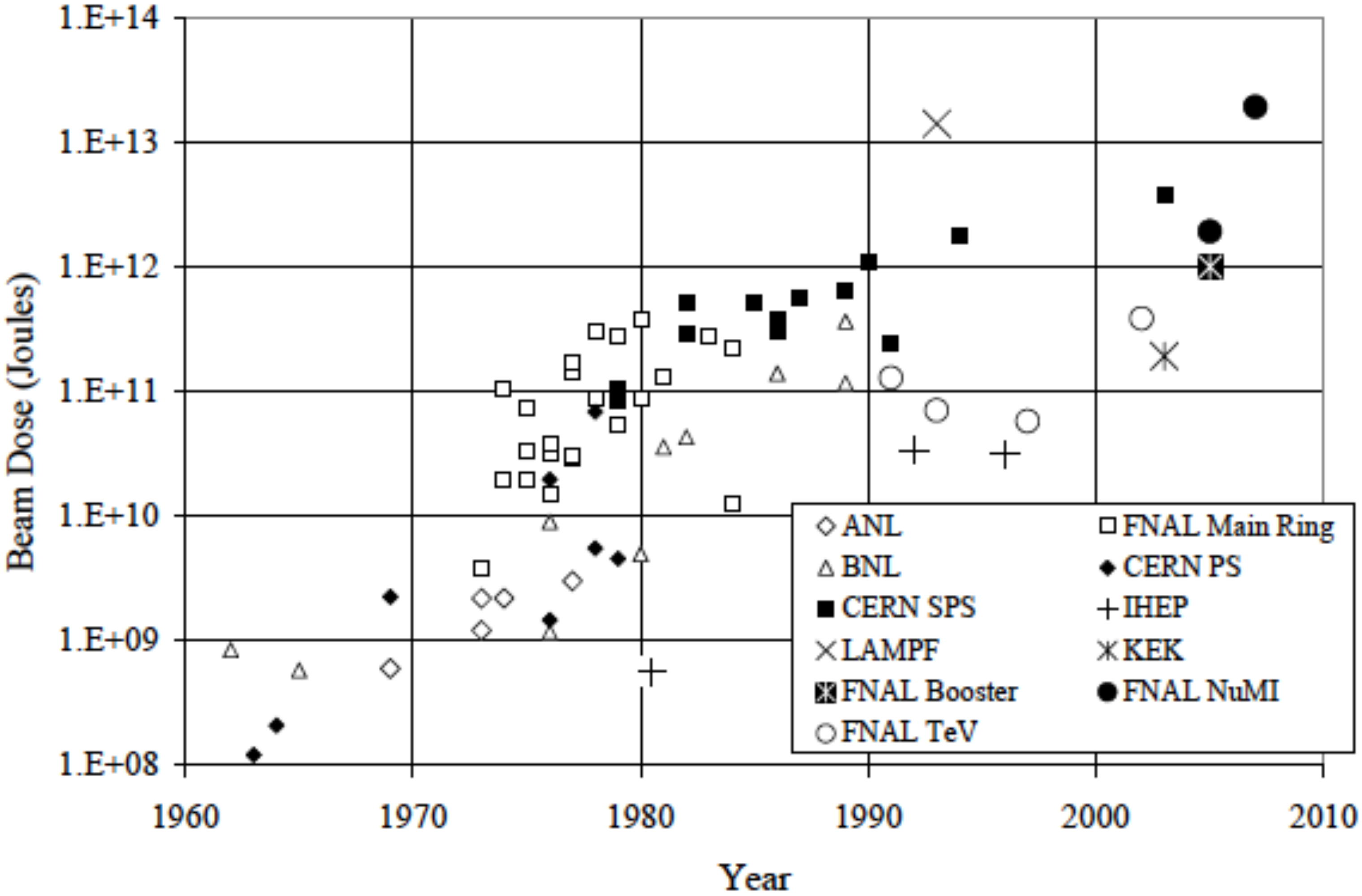
    $K_L \to \pi\mu\nu_{\mu}\ (27.2\%);$
  - Filter to remove π, μ and K: only neutrinos remain

First neutrino beams

- Main problem with AGS beam was low efficiency of extracting secondaries: select only decays at 7.5^o.
- At CERN, neutrino-based accelerator experiments were also developed (1963):
  - Fast extraction of protons from CERN PS at 20.6 GeV
  - Van de Meer invents magnetic horn to focus secondary pions and kaons in forward direction
- Most neutrino beams now extract protons and use some sort of focusing lens, like a horn
- Proton beam power on target has increased since the 1960's – measured as protons-on-target (POT) or as time-integrated power (POT × energy/POT) in Joules

First neutrino beams

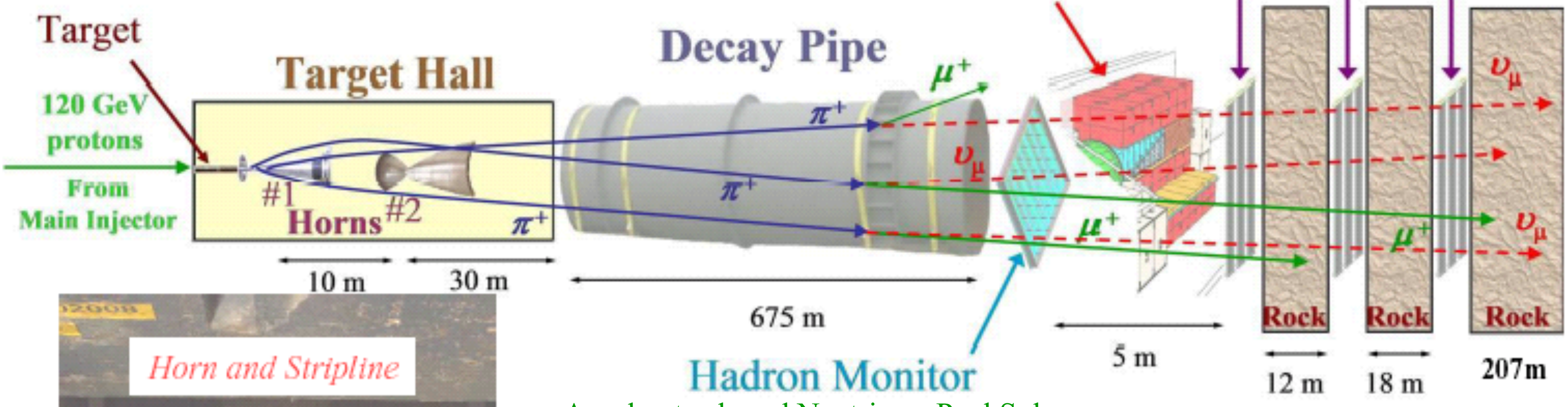
- Total time-integrated power of neutrino beams



Generic neutrino beam

- Design of a neutrino beam from π, K decays:
  - Extraction of proton beam from accelerator
  - Proton beam hits target to create secondary pions, kaons
  - Secondaries are focused by magnetic lenses (horns or others)
  - Secondaries are allowed to decay in decay pipe
  - Absorber material and "beam dump" removes charged particles
  - Detectors along beam line are used to monitor flux and direction

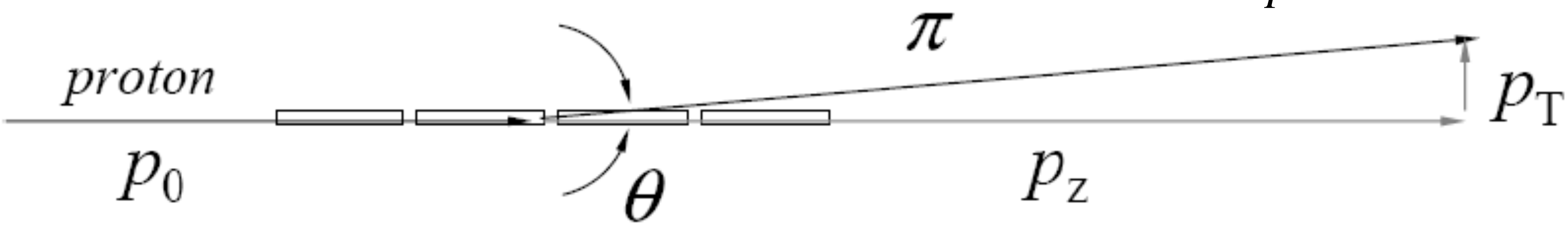
i.e. NuMI Beam at FNAL



1.2 Proton interactions on nuclear targets

Hadron production

- To be able to predict neutrino flux accurately, one needs to understand the production of hadrons from proton interactions: $p + A \rightarrow \pi + X;\ p + A \rightarrow K + X$
  - Need to calculate and measure production yields: $\dfrac{d^2N}{dp\,d\Omega}$



- Hadronic models are built up around simulation packages, such as GEANT3, GEANT4, MARS, FLUKA and/or parameterisations that describe hadron production data
  - Physics models rely on Feynman scaling and p_T invariance:

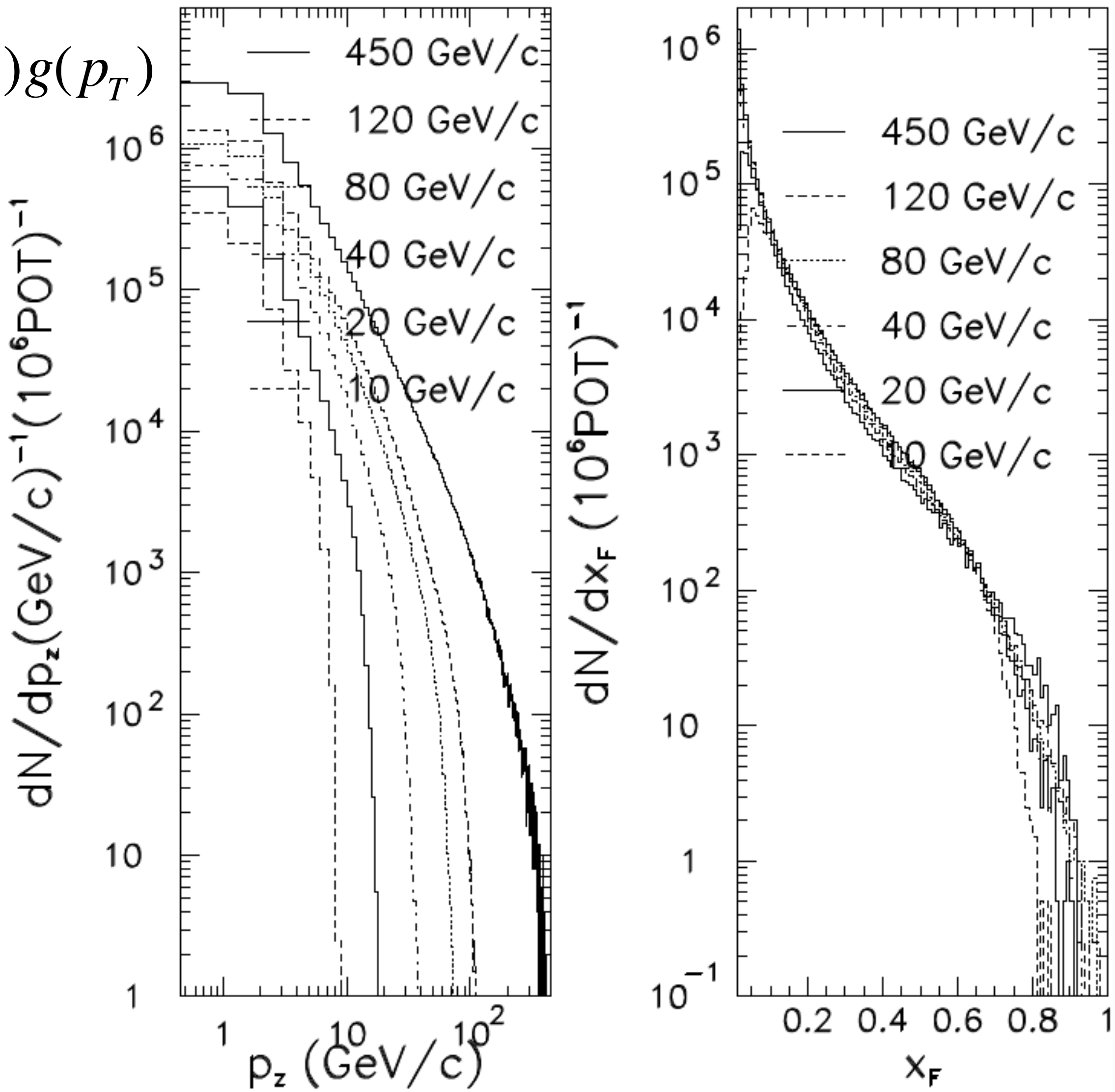
$$\frac{d^2N}{dp\,d\Omega} \approx f(x_F)\,g(p_T) \qquad\qquad x_F = \frac{p_z}{p_0}$$

Hadron production

- FLUKA predictions of: $p + C \rightarrow \pi^{+} + X$

$$\frac{d^2N}{dpd\Omega} \approx f(x_F)g(p_T)$$

$$\langle n_\pi \rangle \propto (p_0)^{0.7}$$

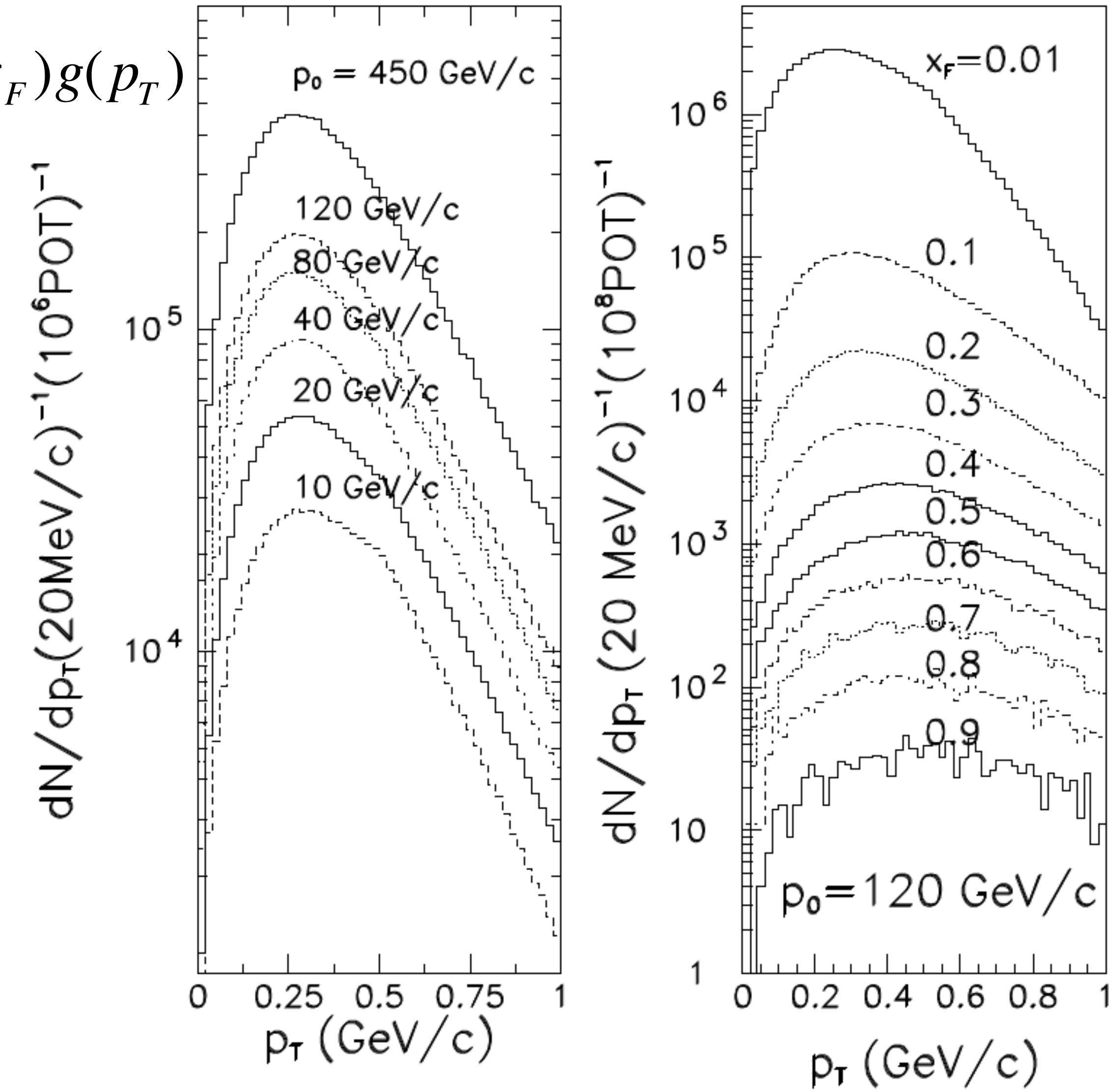


Feynman scaling

Hadron production

- FLUKA predictions of: $p + C \rightarrow \pi^{+} + X$

$$\frac{d^2N}{dpd\Omega} \approx f(x_F)g(p_T)$$

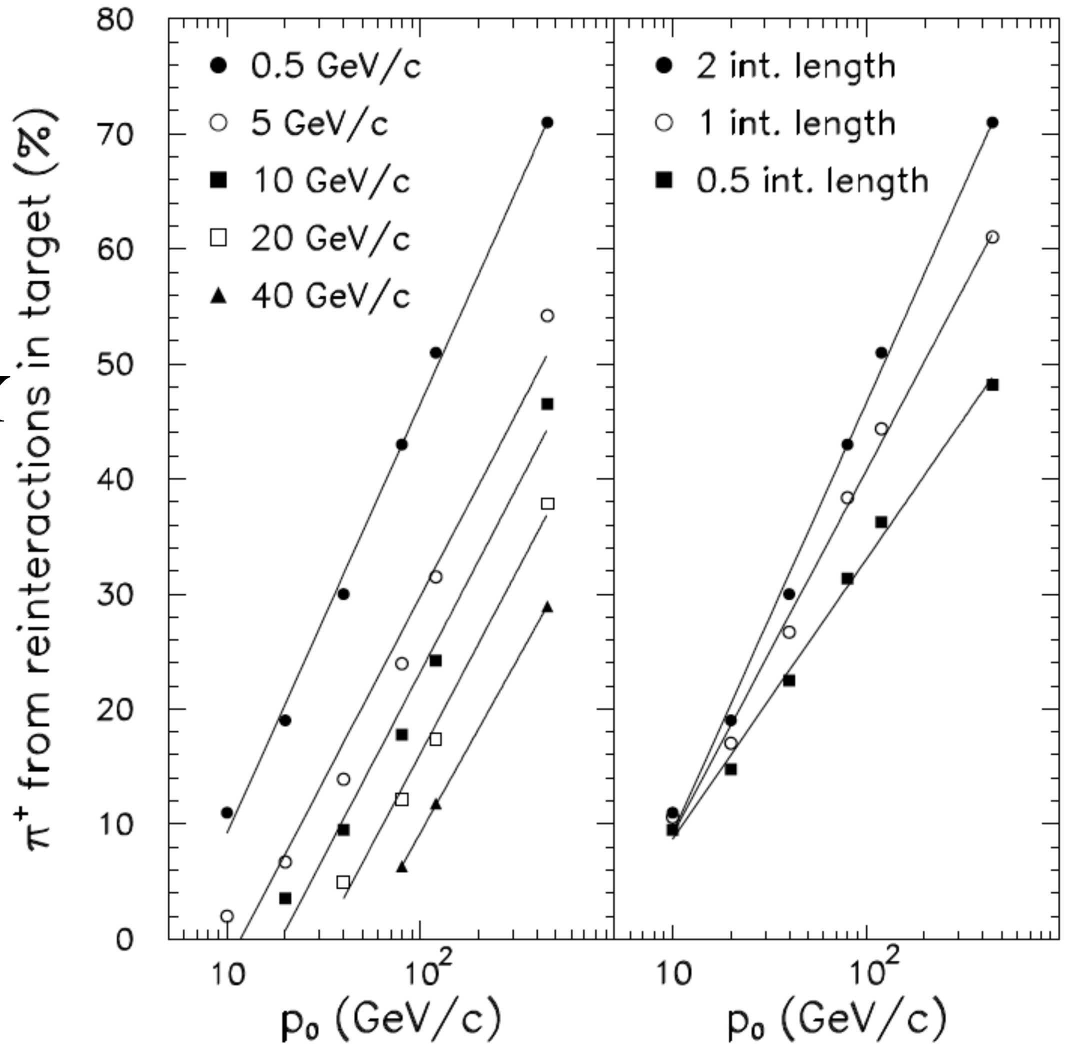


p_T distribution

Hadron production

- For long targets, re-interactions play important role:
  - Re-interactions decrease yield at high E and increase yield low E

$$p + C \rightarrow \pi^+ + X$$



Tertiary π^+ production

Hadron production experiments

- Flux uncertainties in all accelerator-based neutrino experiments from π, K decay rely on accurate knowledge of secondary hadron production.
  - Neutral kaons from quark counting: $N(K_s) = N(K_L) = \frac{1}{4}\left(N_{K^+} + 3N_{K^-}\right)$
- Need experiments to measure hadron production and models that use data to predict yields in all phase space
- Two type of hadron production experiments:
  - Single-arm spectrometers: long spectrometer that measures production on a particle-by-particle basis – mainly 1960-1990s
  - Full acceptance spectrometers, which include a wide acceptance tracking device (ie. TPC), with analysing magnets, complemented by a forward region tracker for low angle scattering (more modern experiments: HARP, NA49, MIPP, NA61/SHINE)
  - Both types of experiments rely on particle identification through dE/dx, Cherenkov and/or Time-of-Flight systems

Hadron production experiments

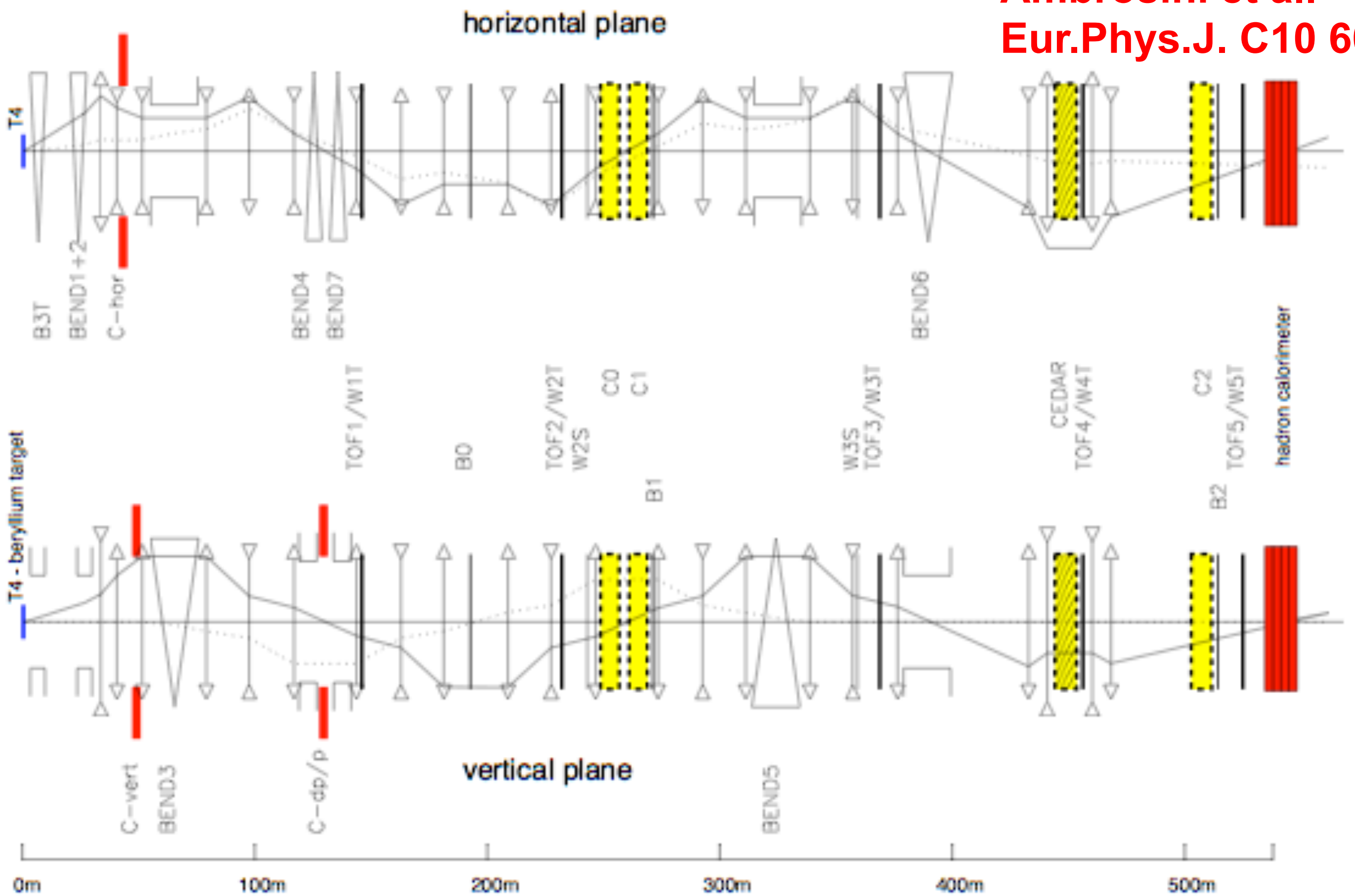
- Summary of hadron production experiments

Reference	p_0 (GeV/c)	Beam	Target Material	t/λ_{int} (in %)	Secondary Coverage
HARP [78]	12	PS	Al	5	$0.75 < p < 6.50$ GeV/c, $30 < \theta < 210$ mrad [d]
Asbury[25]	12.5	ANL	Be	4.9, 12.3	p =3, 4, 5, $\theta = 12°, 15°$
Cho [81]	12.4	ANL	Be	4.9, 12.3	$2 < p < 6$ GeV/c, $0° < \theta < 12°$
Lundy[149][a]	12.4	ANL	Be	25,50,100	$1 < p < 12$ GeV/c, $2° < \theta < 16°$
Marmer[156]	12.3	ANL	Be, Cu	10	p =0.5, 0.8, 1.0 GeV/c, $\theta = 0°, 5°, 10°$
Abbot [11]	14.6	AGS	Be, Al, Cu, Au	1.0-2.0	$0 < p < 8$ GeV/c, $\theta = 5°, 14°, 24°, 34°, 44°$
Allaby [17]	19.2	PS	Be, Al, Cu, Pb, B_4C	1-2	p =6, 7, 10, 12, 14 GeV/c, θ =12.5, 20, 30, 40, 50, 60, 70 mrad
Dekkers [88][b]	18.8, 23.1	PS	Be, Pb	"thin"	$1 < p < 12$ GeV/c, $\theta = 0, 100$ mrad
Eichten [99]	24	PS	Be, Al, Cu, Pb, B_4C	1-2	$4 < p < 18$ GeV/c, $17 < \theta < 127$ mrad
Baker [31]	10,20,30	AGS	Be, Al	??	$1 < p < 17$ GeV/c, $\theta = 4.75°, 9°, 13°, 20°$
Barton[48]	100	FNAL	C,Al,Cu,Ag,Pb	1.6-5.6	$0.3 < x_F < 0.88$, $0.18 < p_T < 0.5$ GeV/c
NA49 [21]	158	SPS	C	1.5	$0.05 < p_T < 1.8$ GeV/c, $-0.1 < x_F < 0.5$[c]
Aubert [30]	300	FNAL	Al	76	$\theta = 0.8$ mrad, x_F =0.083, 0.17, 0.25, 0.33, 0.42, 0.5, 0.58, 0.67, 0.0.75
Baker [32]	200, 300	FNAL	Be	50	$\theta = 3$ mrad[d], $60 < p < 370$ GeV/c
Baker [33]	400	FNAL	Be	75	$\theta = 3.6$ mrad, $23 < p < 197$ GeV/c
Atherton[29]	400	SPS	Be	10,25,75,125	x_F =0.15, 0.30, 0.50, 0.75, p_T =0, 0.3, 0.5 GeV/c
NA56/SPY [22]	450	SPS	Be	25,50,75	x_F =0.016, 0.022, 0.033, 0.044, 0.067, 0.089, 0.15, 0.30, p_T=0, 75, 150, 225, 375, 450, 600 MeV/c

Hadron production experiments

- Example of a single-arm spectrometer: NA56/SPY
  - Measured 450 GeV protons on Beryllium target for CERN West Area neutrino Facility (WANF) for NOMAD and CHORUS expts

Ambrosini et al. Eur.Phys.J. C10 605 (1999)

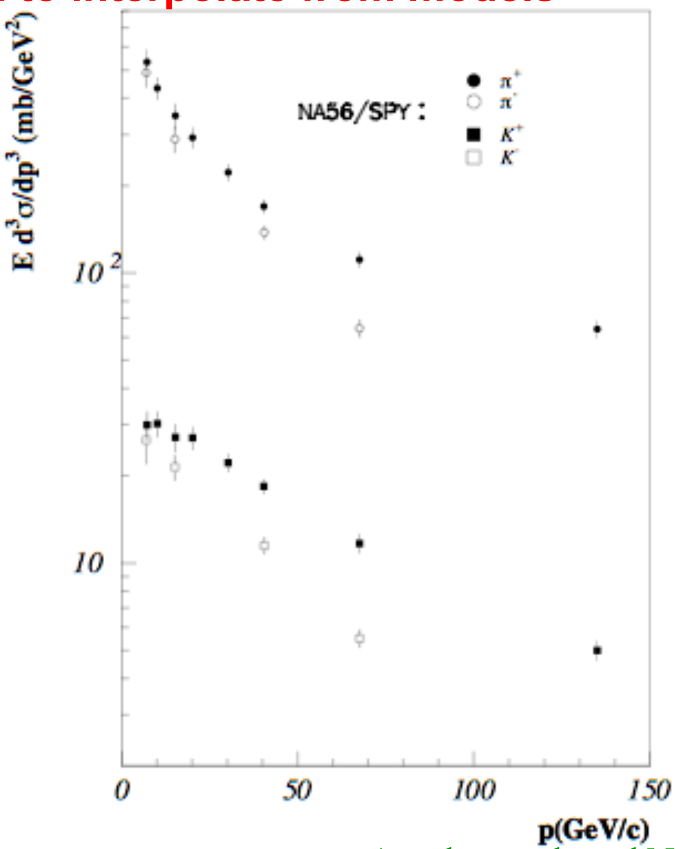


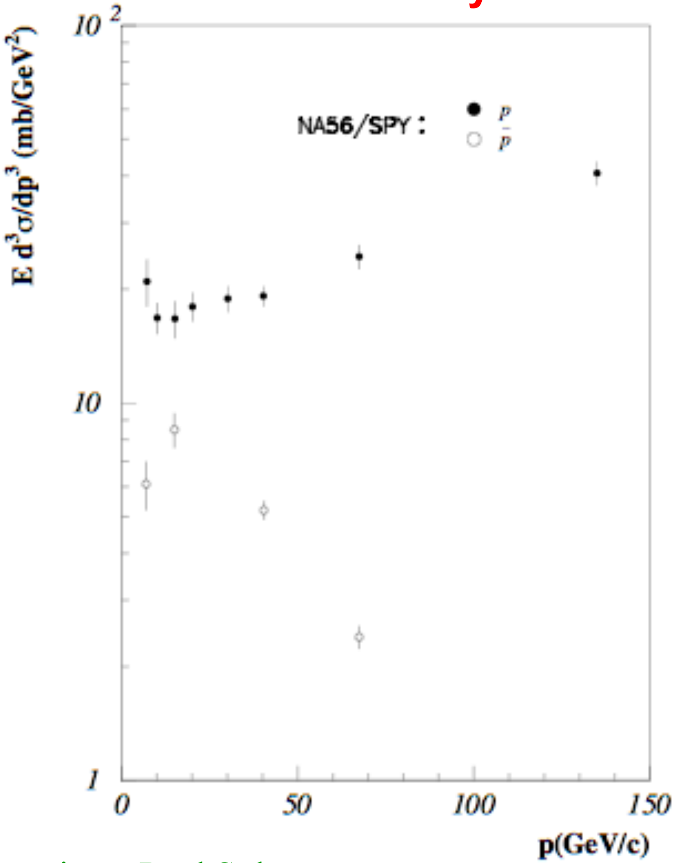
Hadron production experiments

- Example of a single-arm spectrometer: NA56/SPY (~1995)
  - Measured 450 GeV protons on Beryllium target for CERN West Area neutrino Facility (WANF) for NOMAD and CHORUS expts

Sparsely populated data
Need to interpolate from models

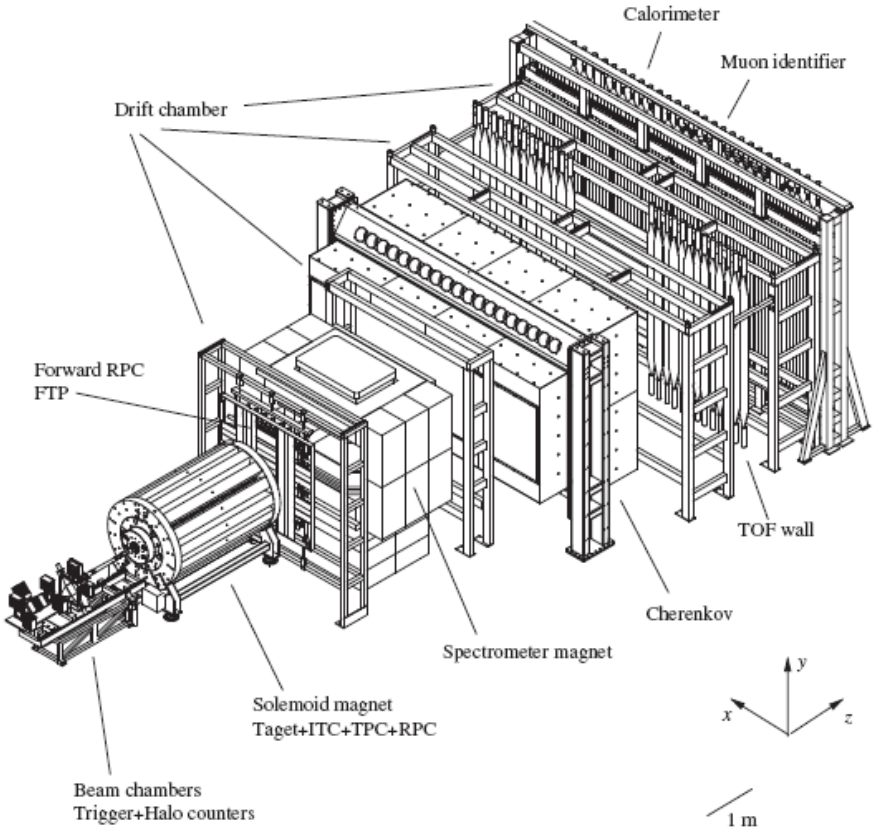
Ambrosini et al.
Eur.Phys.J. C10 605 (1999)

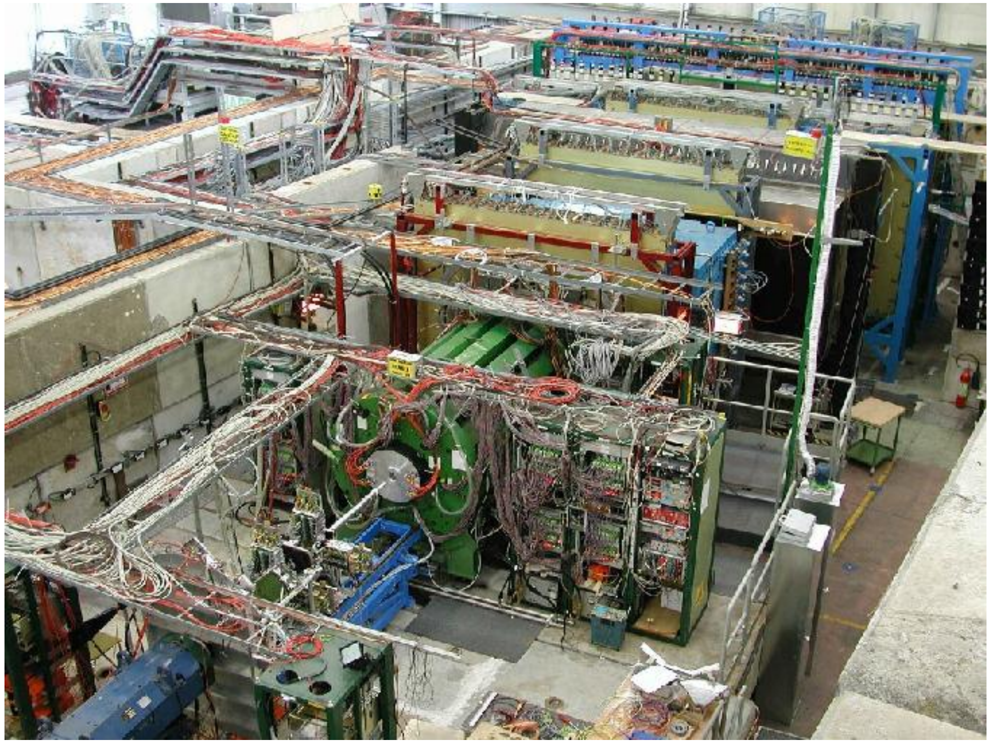




Hadron production experiments

- Example of wide-angle spectrometer: HARP (2002-2003)
  - Measured 3-12.9 GeV protons on Be, C, Al, Cu, Sn, Pb, H_2, O_2, N_2 targets at CERN – also did replica K2K and MiniBooNE targets





HARP Measurements

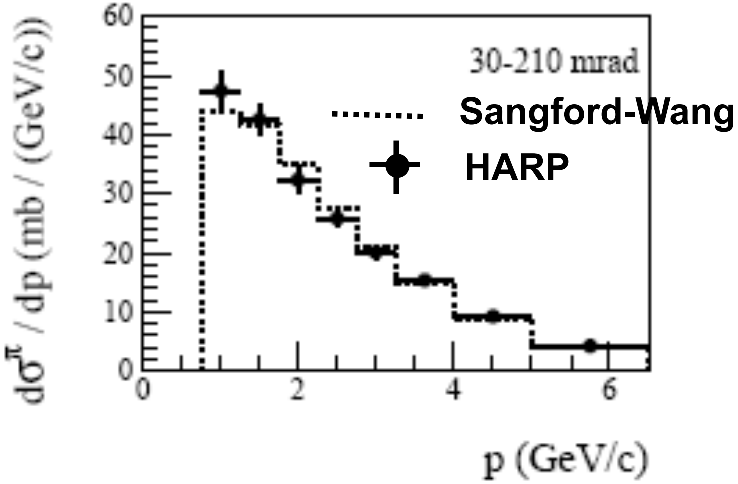
- Differential cross-section definition used in HARP analysis:

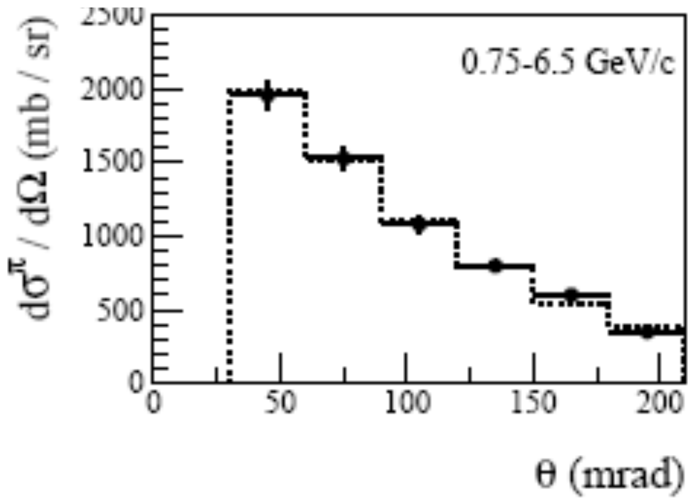
$$\frac{d^2\sigma_\alpha}{dp_i d\theta_j} = \frac{1}{N_{pot}} \frac{A}{N_A \rho\, t} M^{-1}_{ij\alpha i'j'\alpha'} N^{\alpha'}_{i'j'}$$

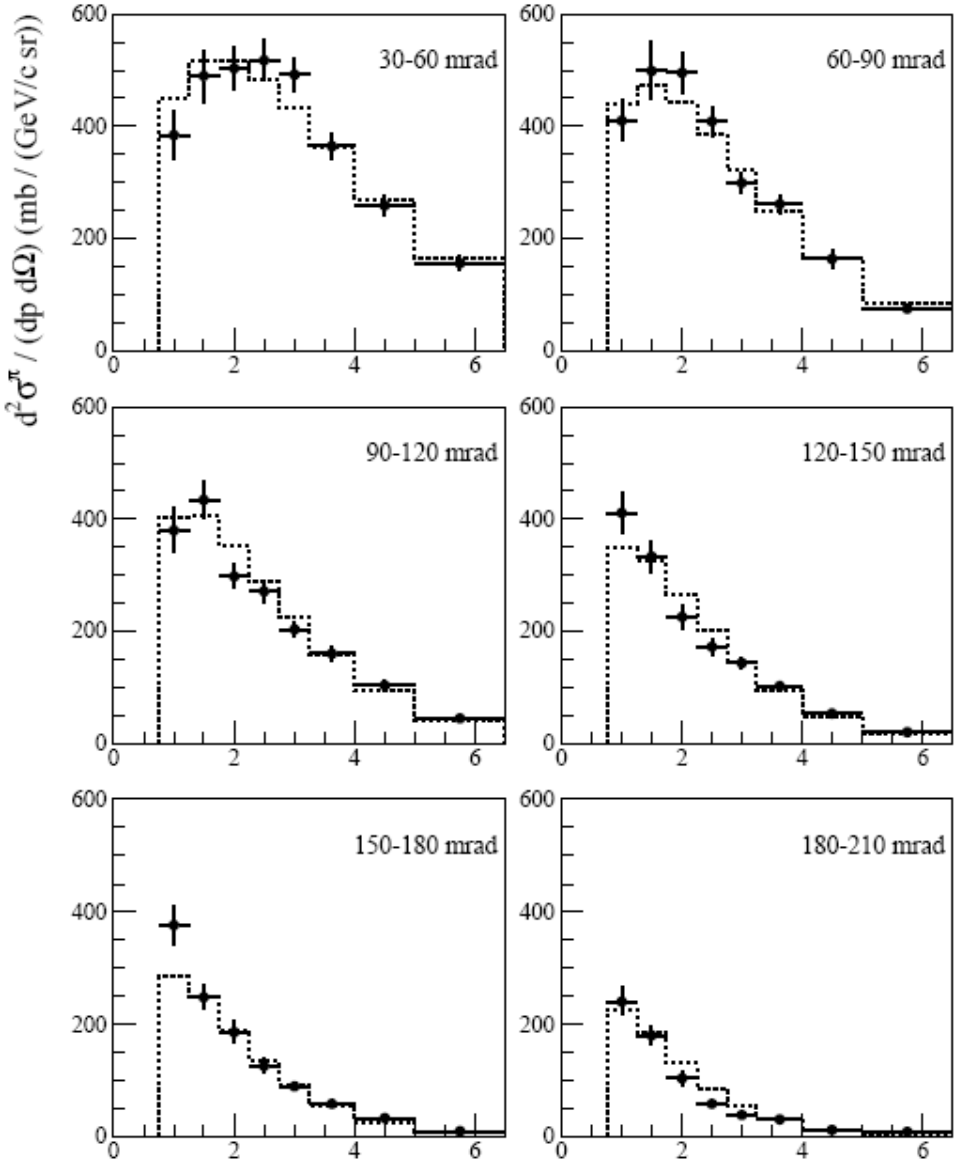
  - Number protons: N_{pot}
  - Target nuclei per unit area: $\frac{A}{N_A \rho\, t}$
  - Number of observed particles of type α' in momentum bin $p_{i'}$ and angle $\theta_{j'}$: $N^{\alpha'}_{i'j'}$
  - Inverse of correction matrix that corrects for detector efficiency and resolution: $M^{-1}_{ij\alpha i'j'\alpha'}$

HARP Pion results for K2K

- Differential cross-sections: 12.9 GeV/c protons on 5% Λ_I aluminium





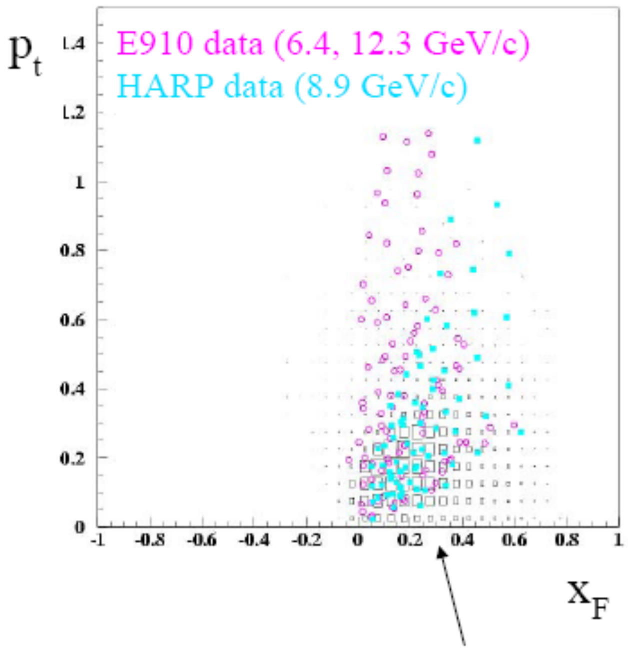


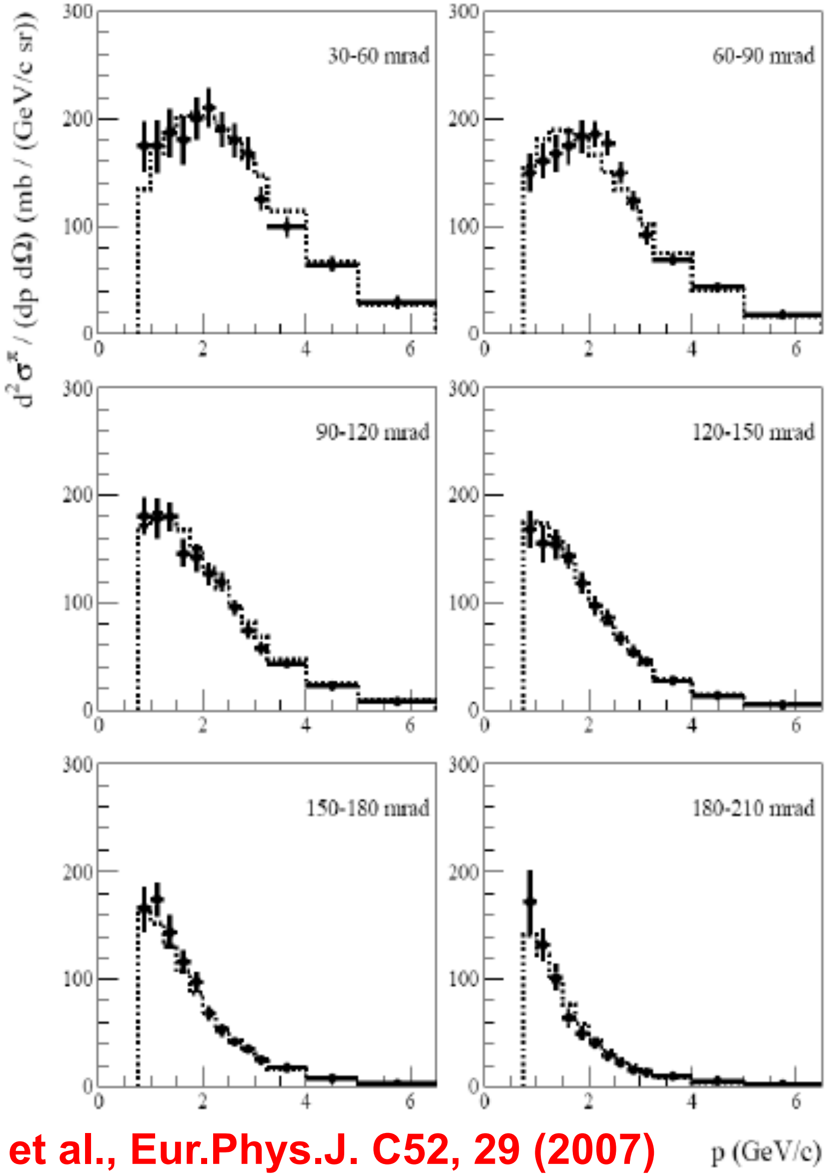
Catanesi et al., Nucl.Phys. B732, 1 (2006)

p (GeV/c)

HARP data for MiniBooNE

- π^+ production from 8.9 GeV/c protons on 5% Λ_I Be target :
  - Sangford-Wang parametrization
  - 8.9 GeV/c protons
  - 5% Λ_I Be target
  - Inclusion also of E910 data at 6.4 GeV/c and 12.3 GeV/c

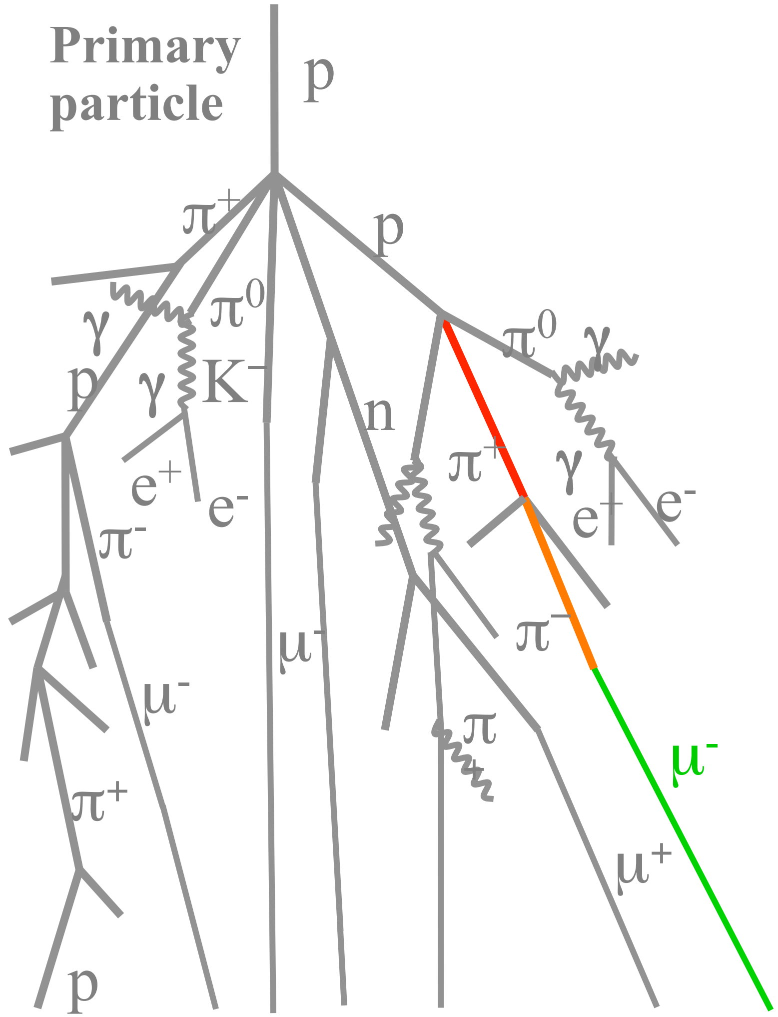


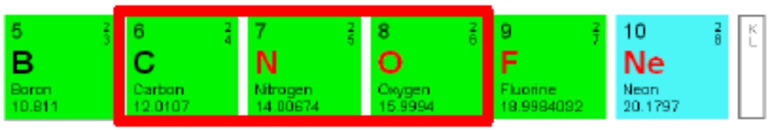


Catanesi et al., Eur.Phys.J. C52, 29 (2007)

Atmospheric Neutrinos, EAS and HARP

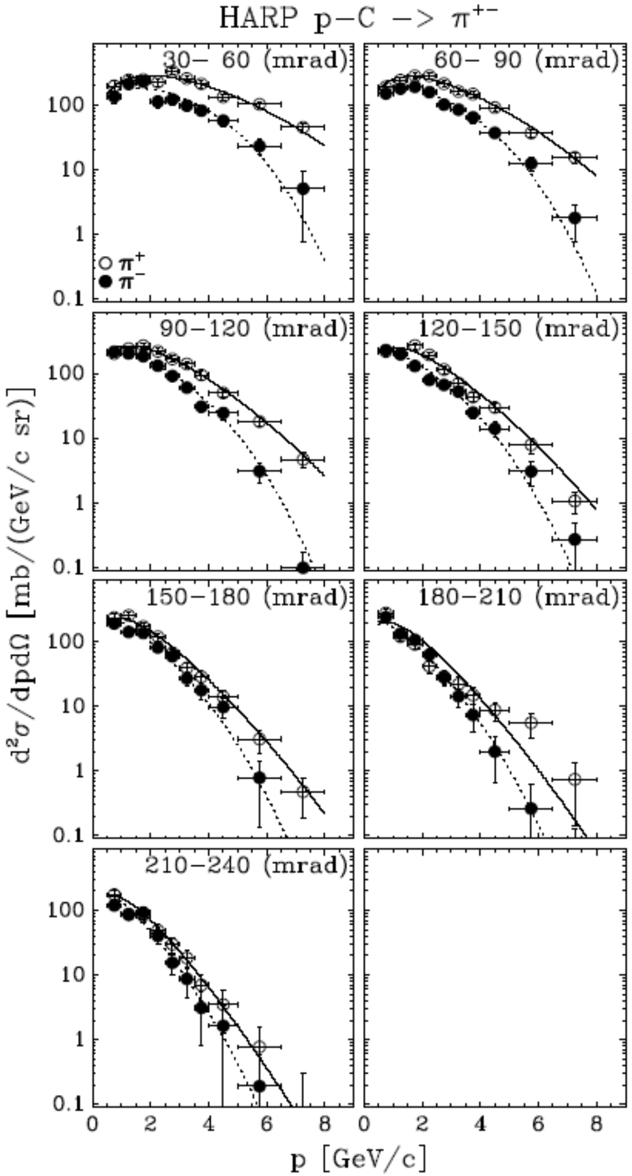
- Atmospheric neutrinos and extended air shower (EAS) flux calculations rely on hadronic models:
  - Primary flux (70% p, 20% He, 10% heavier nuclei) is known to better than 15%
  - Most uncertainty comes from hadron interaction model.
- Model-dependent extrapolations from the limited set of data leads to about 30% uncertainty in atmospheric fluxes
- → cryogenic targets (O_2 and N_2 and compare to nearby C data)

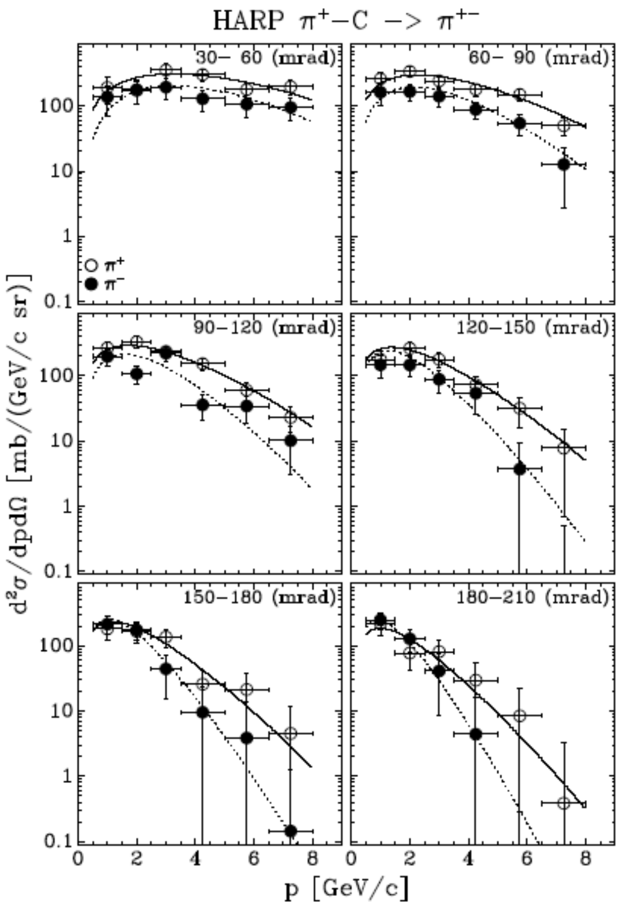


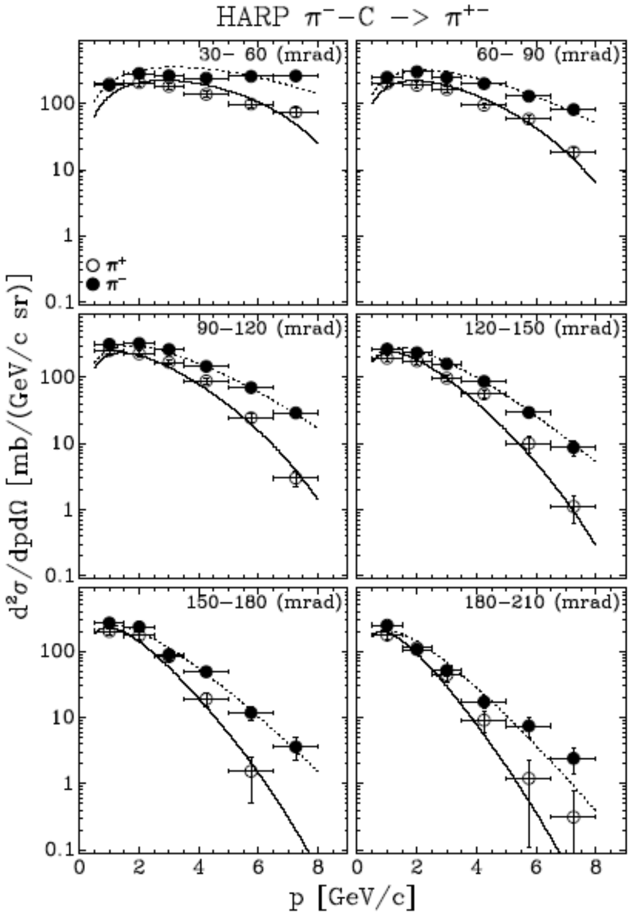


78% nitrogen
21% oxygen

HARP data p,$\pi^{\pm}$ on C

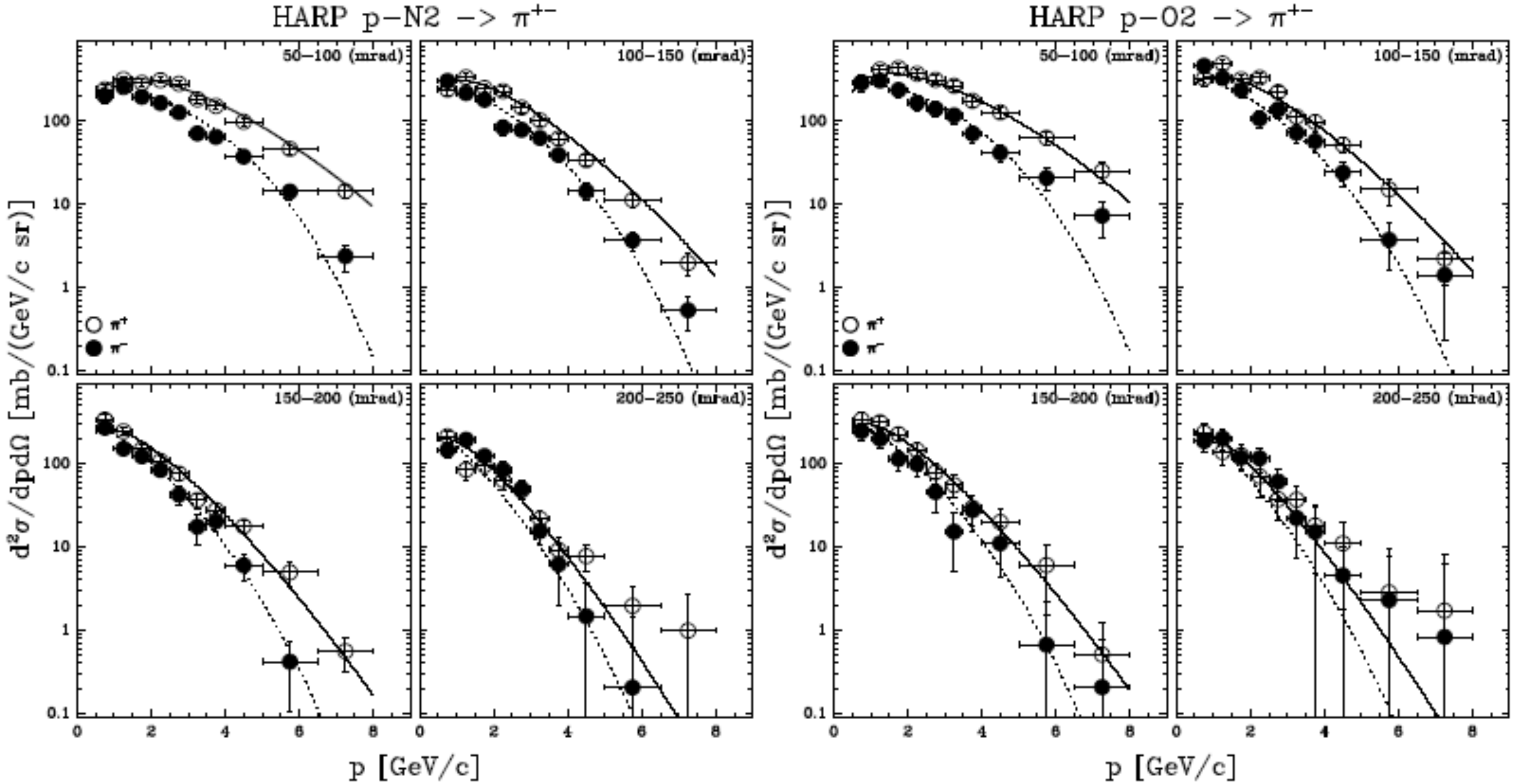






Astroparticle Physics 29 (2008), 257-281.

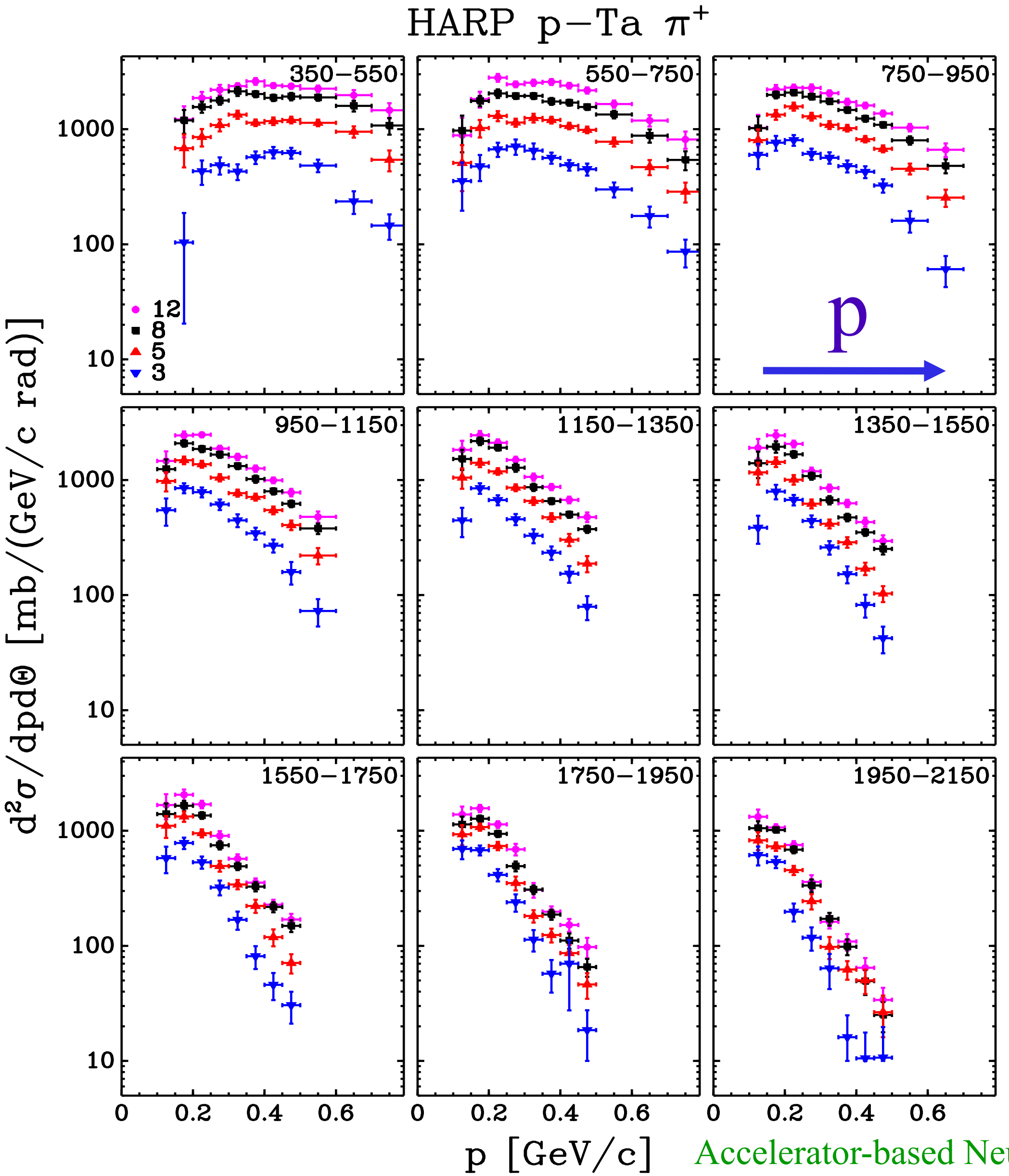
HARP data p,$\pi^{\pm}$ on O_2 and N_2



Astroparticle Physics 30 (2008), 124-132

First ever result with O_2 and N_2

Large angle HARP analysis: π^+ from p -Ta

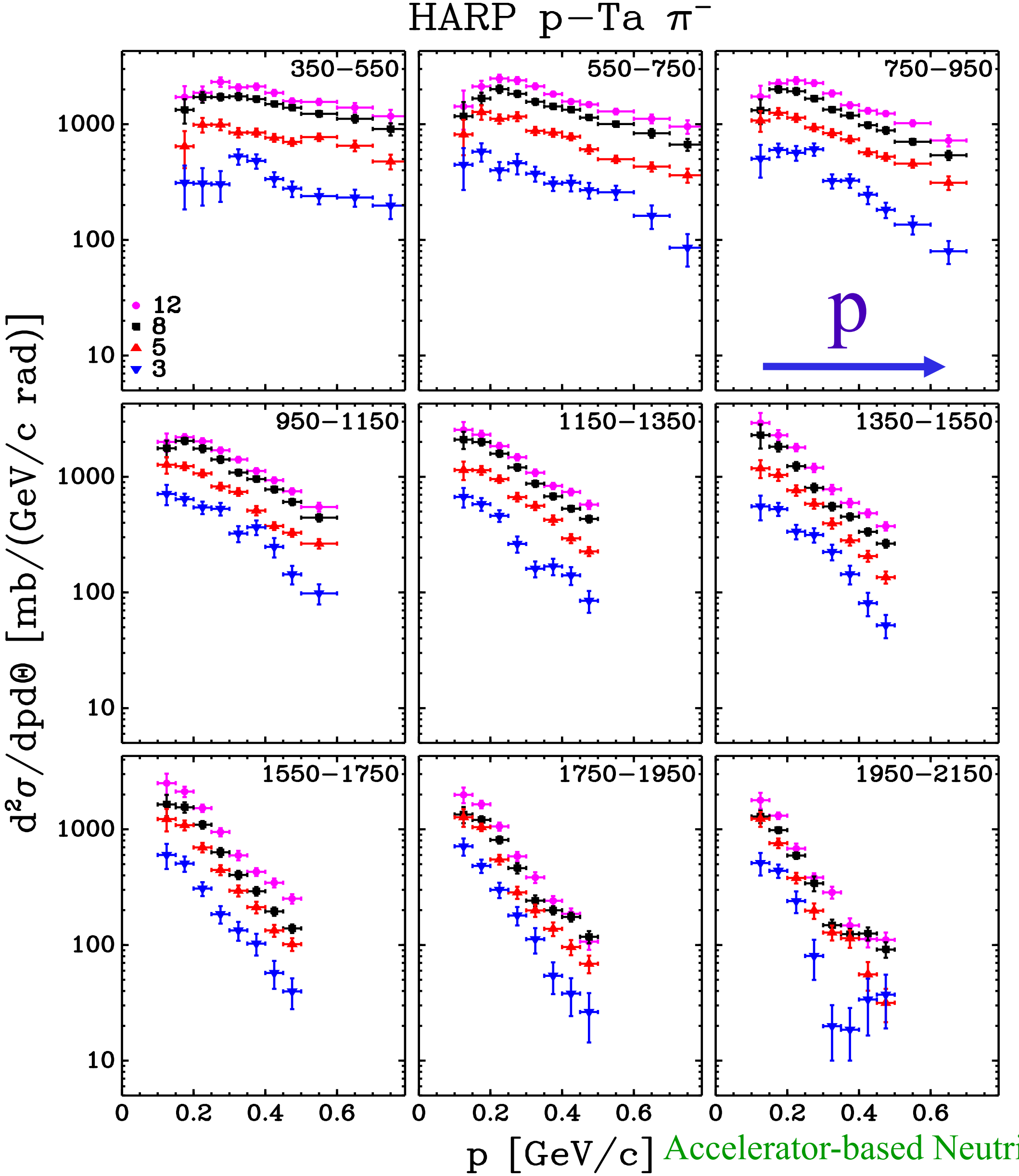


- Tantalum (Z=73): potential neutrino factory solid target, close to Hg (Z=80)

Forward
$0.35 < \theta < 1.55$

Backward
$1.55 < \theta < 2.15$

Large angle HARP analysis: π^- from p -Ta



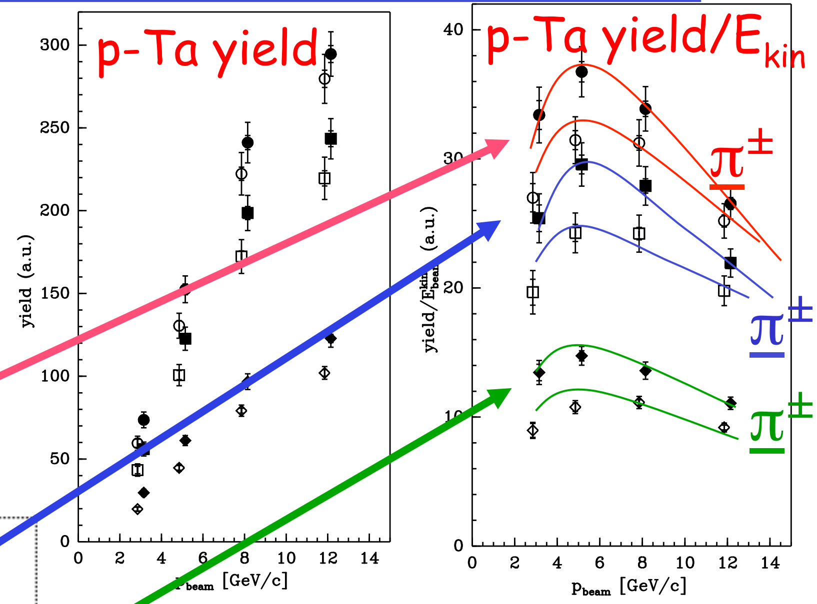
- Tantalum (Z=73): potential neutrino factory solid target, close to Hg (Z=80)

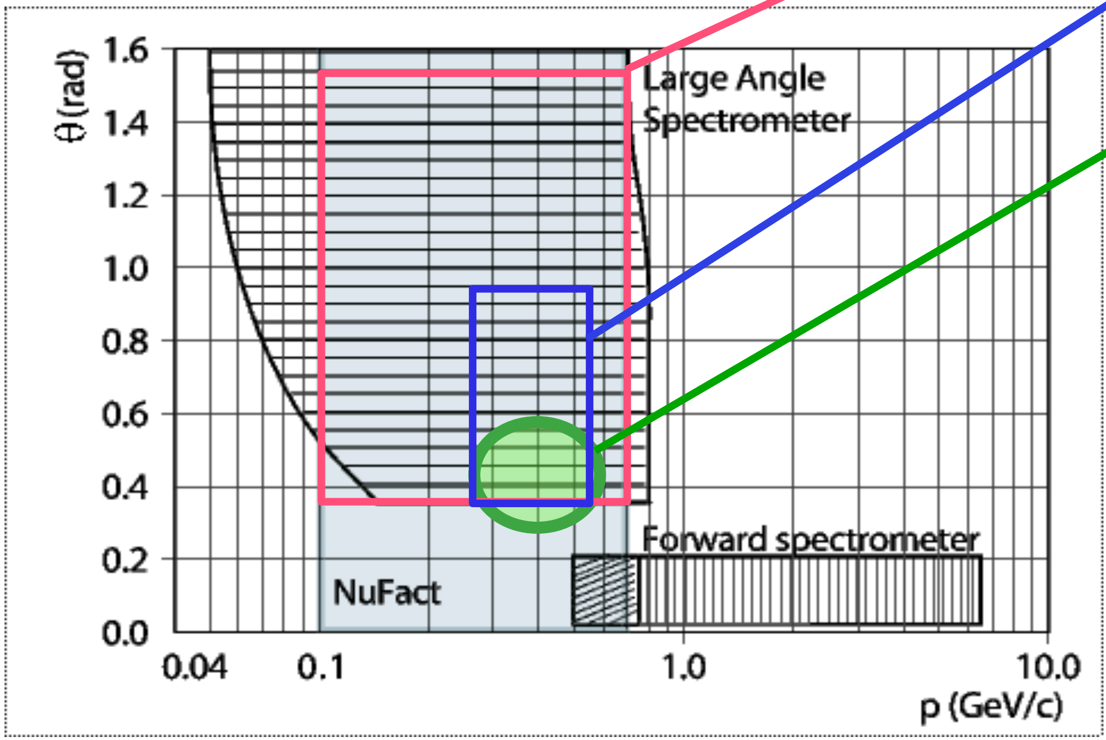
Forward
$0.35 < \theta < 1.55$

Backward
$1.55 < \theta < 2.15$

Neutrino Factory consequences

- Different assumptions about neutrino factory front-end depending on momentum and angular acceptance



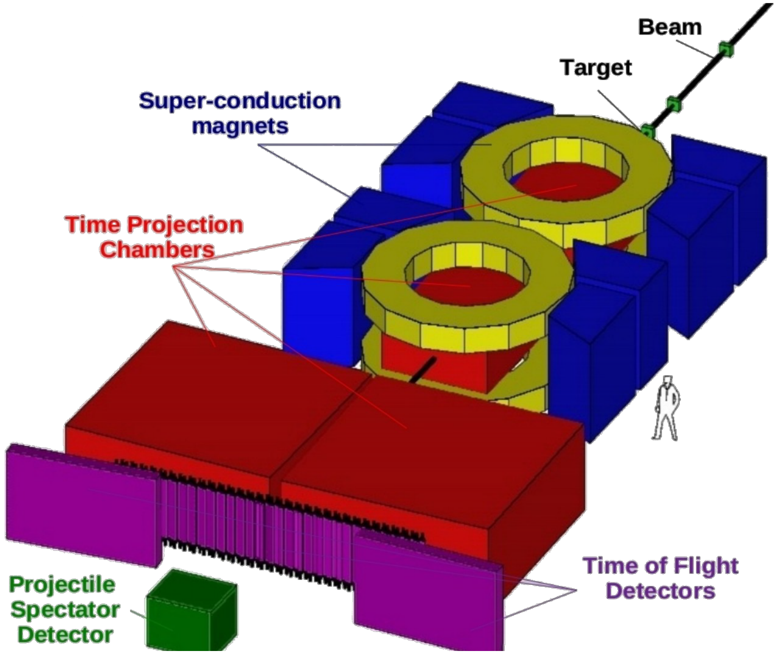


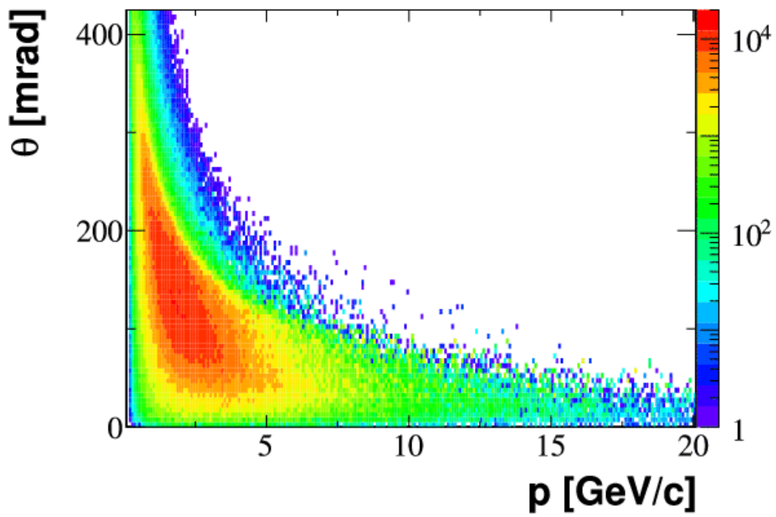
Cross-sections to be fed into neutrino factory studies to find optimum design: Ta and Pb x-sections at large angle (see Eur. J. Phys C51 (2007) 787)

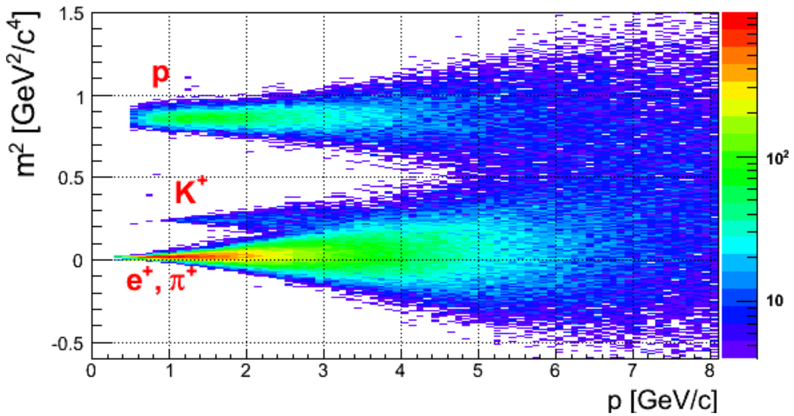
NA61/SHINE

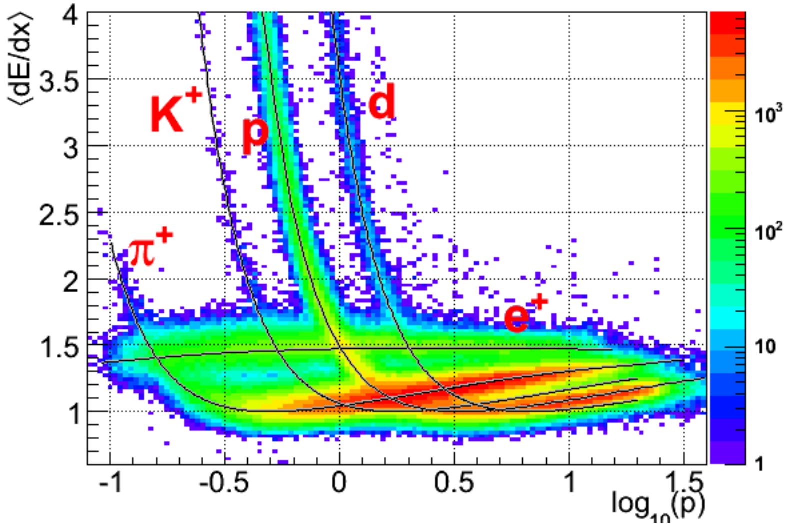
- NA61/SHINE experiment took data of 31 GeV/c protons on C for T2K flux determination

Korsenev, EPS-HEP (2013), Stockholm





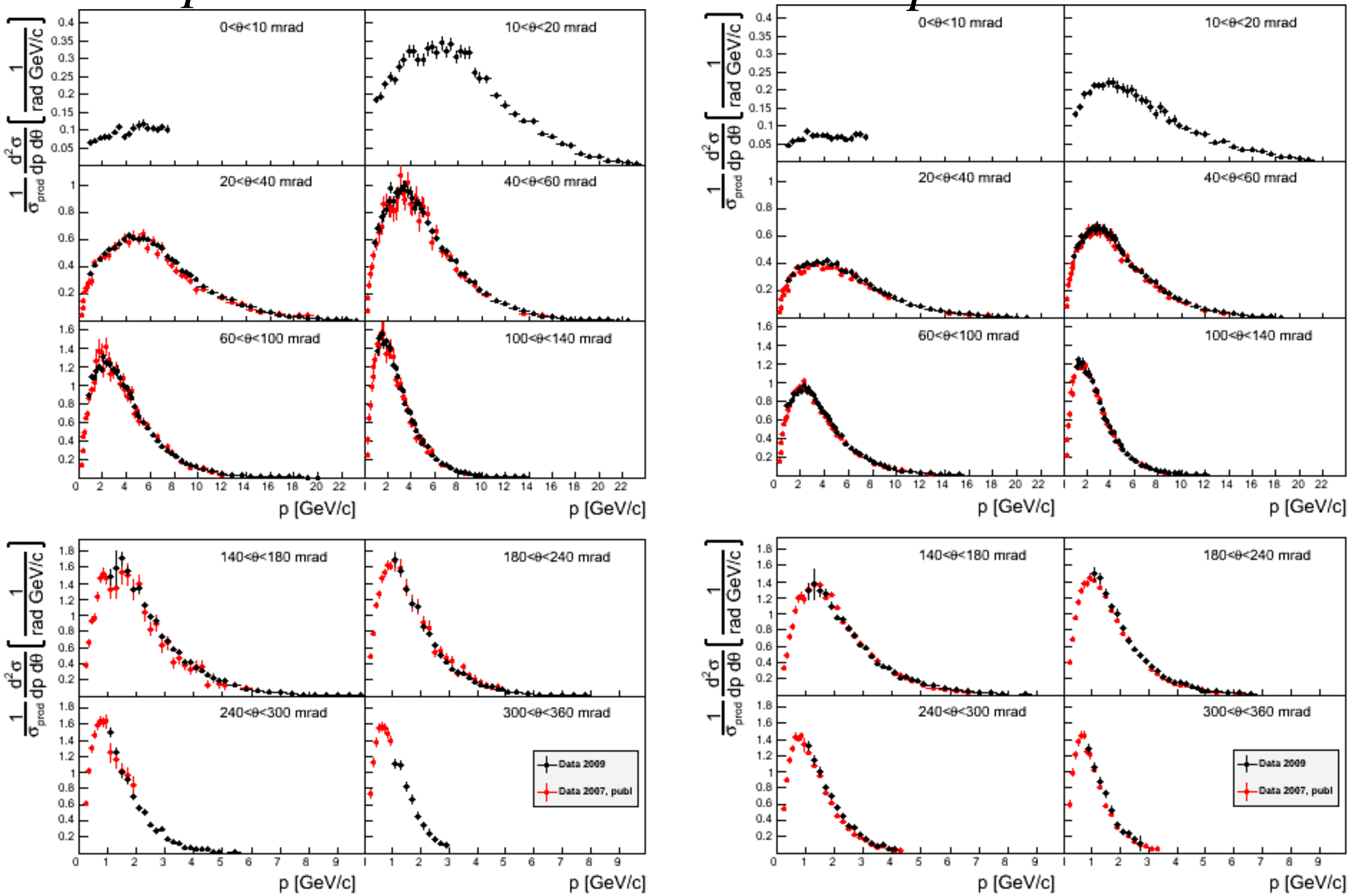




NA61/SHINE

- NA61/SHINE experiment took data of 31 GeV/c protons on C for T2K flux determination **Korsenev, EPS-HEP (2013), Stockholm**

$p + C \rightarrow \pi^{+} + X$ $\qquad$ $p + C \rightarrow \pi^{-} + X$



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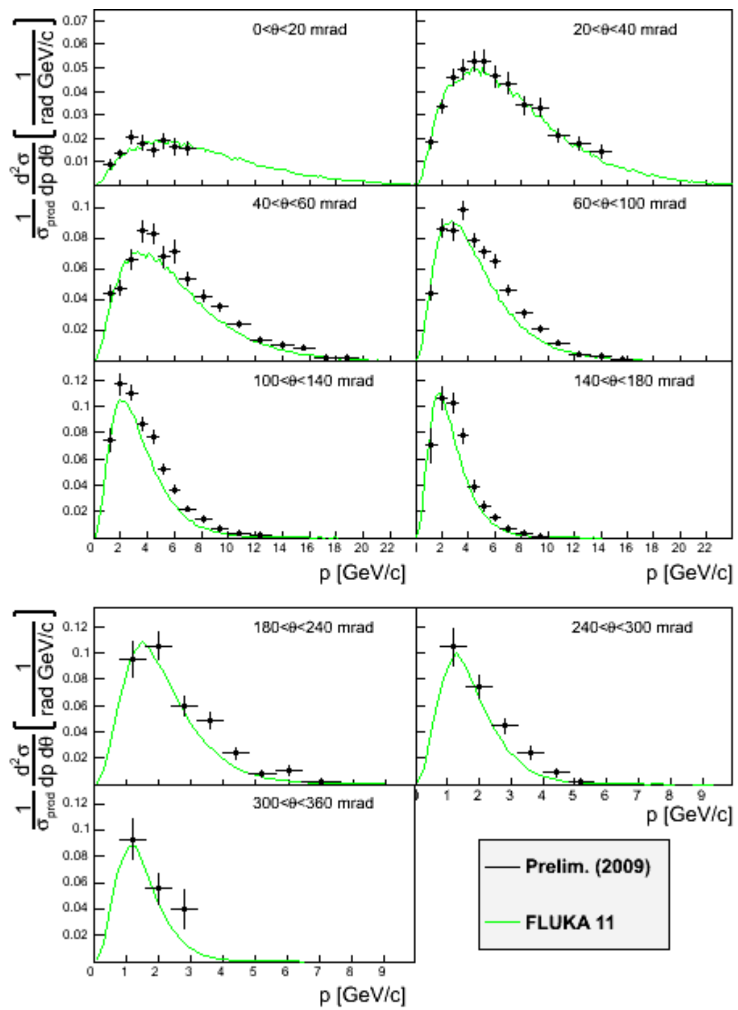
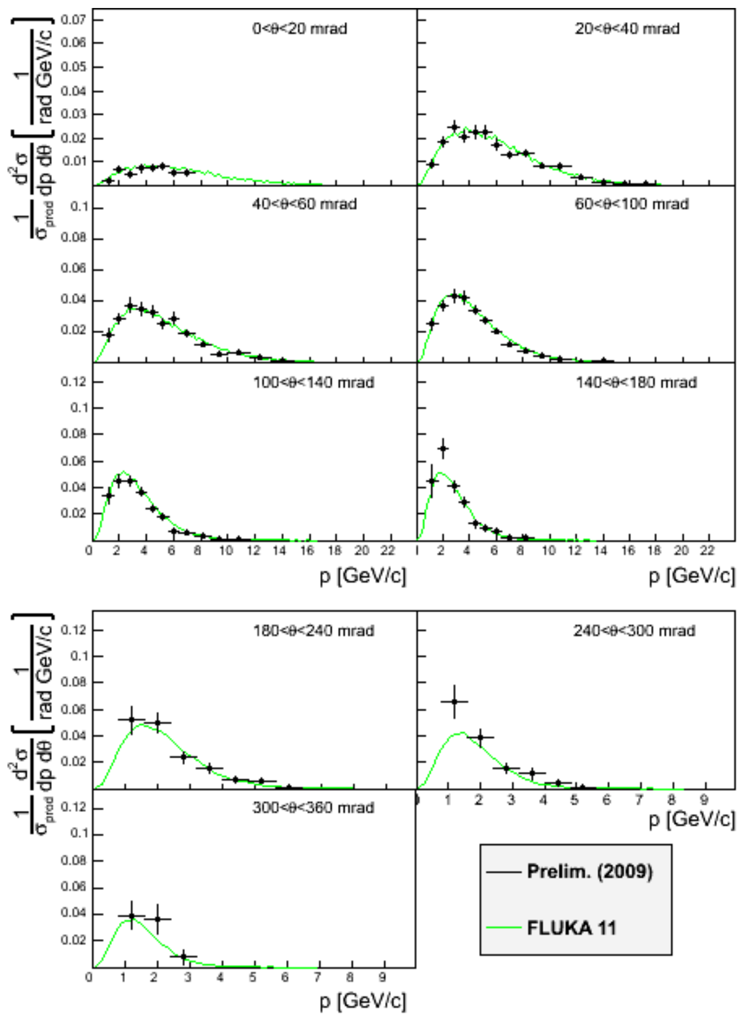
Korsenev, EPS-HEP (2013), Stockholm

$$p + C \rightarrow K^{+} + X$$



$$p + C \rightarrow K^{-} + X$$



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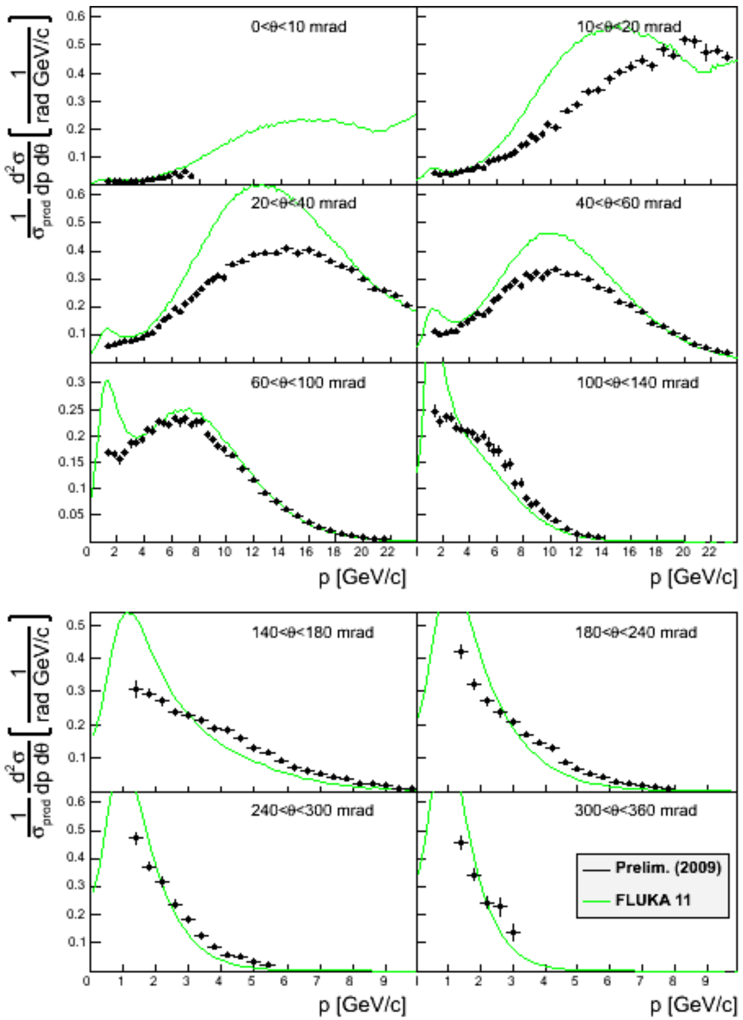
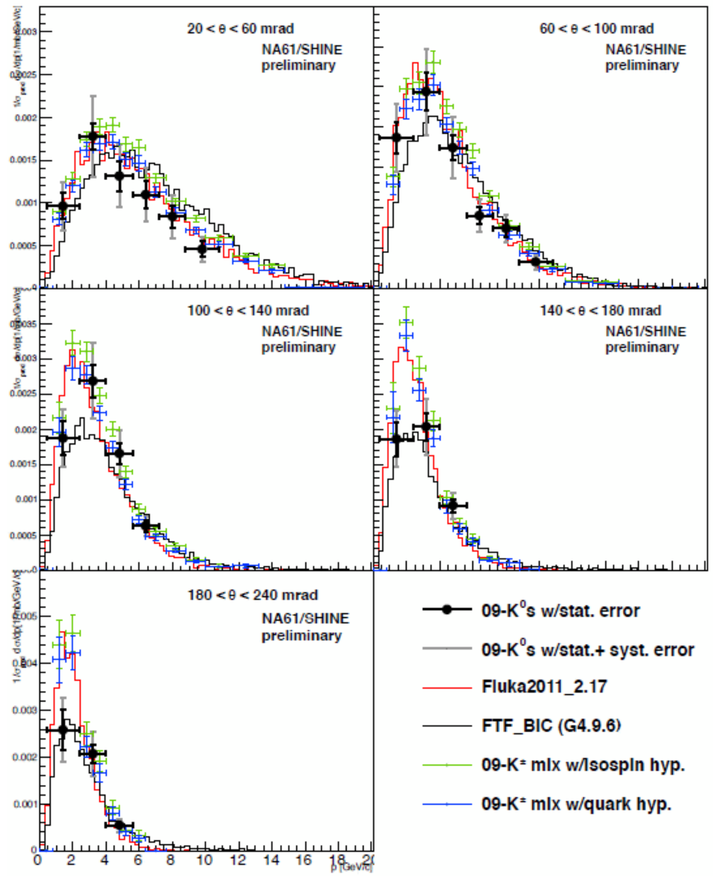
$$p + C \rightarrow p + X$$



$$p + C \rightarrow K_s + X$$



Hadron production parametrisations

- Shower cascade Monte Carlo models required: MARS and FLUKA are tuned to data and are quite successful
- Parametric models:
  - Malensek: fit to Atherton et al. data but failed to fit NA56/SPY

$$\frac{d^2N}{dpd\Omega} = Kp(1-x_F)^A \frac{\left(1+5e^{-Dx_F}\right)}{\left(1+p_T^2/m^2\right)^4}$$

  - BMPT: extension of Malensek to fit NA56/SPY data

$$\left(E \times \frac{d^3\sigma}{dp^3}\right) = A(1-x_F)^{\alpha} x_R^{-\beta}\left(1+a'(x_R)p_T + b'(x_R)p_T^2\right)e^{-a'(x_R)p_T}$$

  - Sanford-Wang: used for low energies, ie. HARP, MiniBooNE, K2K

$$\frac{d^2N}{dpd\Omega} = Ap^B(1-p/p_0)\exp\left[-\frac{cp^D}{p_0^E} - F\theta\left(p - Gp_0\cos^H\theta\right)\right]$$

  - CKP: from old cosmic ray data $\frac{d^2N}{dpd\Omega} = Ap^2(p_0-p)e^{-(p-a)(b+c\theta)}$

1.3 Magnetic focusing systems

Meson decays

- We calculate pion and kaon decay from kinematics:
  - Momentum of daughters: $$p' = \frac{m_\pi}{2}\left(1 - \frac{m_\mu^2}{m_\pi^2}\right)$$
  - Lorentz boost: $$\begin{cases} E = \gamma\left(E' + \beta p'_z\right) \\ p_z = \gamma\left(p'_z + \beta E'\right) \\ p'_T = p'_T \end{cases}$$
  - In CM frame (spin=0): $$\frac{dP}{d\Omega'} = \frac{1}{4\pi}$$
  - In LAB frame: $$\frac{dP}{d\Omega} = \frac{1}{4\pi}\frac{4\gamma^2\left(1+\tan^2\theta\right)^{3/2}}{\left(1+\gamma^2\tan^2\theta\right)^2}$$
  - At small angles the neutrino flux is: $$\phi_\nu = \frac{A}{4\pi z^2}\left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2$$
  - Without focusing, pions diverge: $$\theta_\pi \approx \frac{\langle p_T\rangle}{p} = \frac{280\ MeV}{\gamma m_\pi} = \frac{2}{\gamma}$$
  - Neutrino angle with respect to pion ~1/γ, less than π angle

Van der Meer Horn

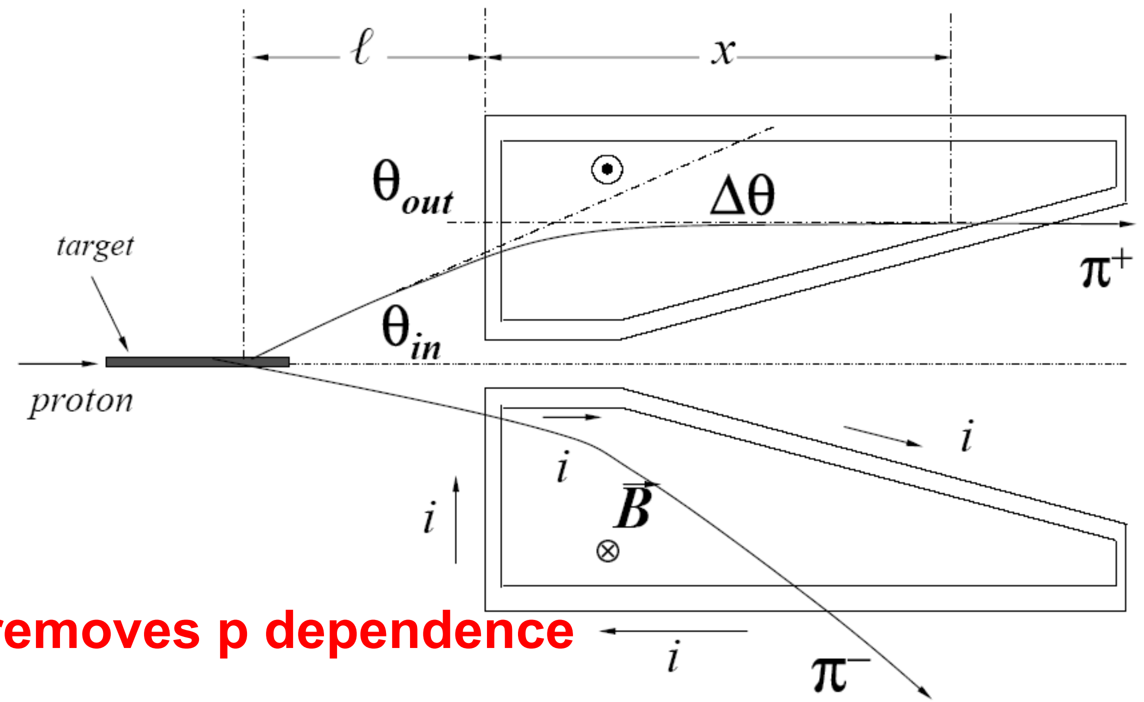
- Perfect pion focusing could increase flux by factor of 25
- Simon van der Meer invented "magnetic conical horn" in 1961 to increase collection of secondary pions and kaons
  - Two conductors produce toroidal field: $B = \frac{\mu_0 I}{2\pi r}$
  - Focuses pions of one sign and defocuses the other sign.

$$\theta_{in} = \frac{r}{l}$$

$$\Delta\theta = \frac{Bx}{p} = \frac{\mu_0 I}{2\pi r}\frac{x}{p}$$

$$\Delta\theta = \overline{\theta}_{in} \approx \frac{\langle p_T \rangle}{p}$$

$$\Rightarrow x = \langle p_T \rangle \frac{2\pi}{\mu_0 I} r$$



Conical geometry removes p dependence

Broad-band beam!

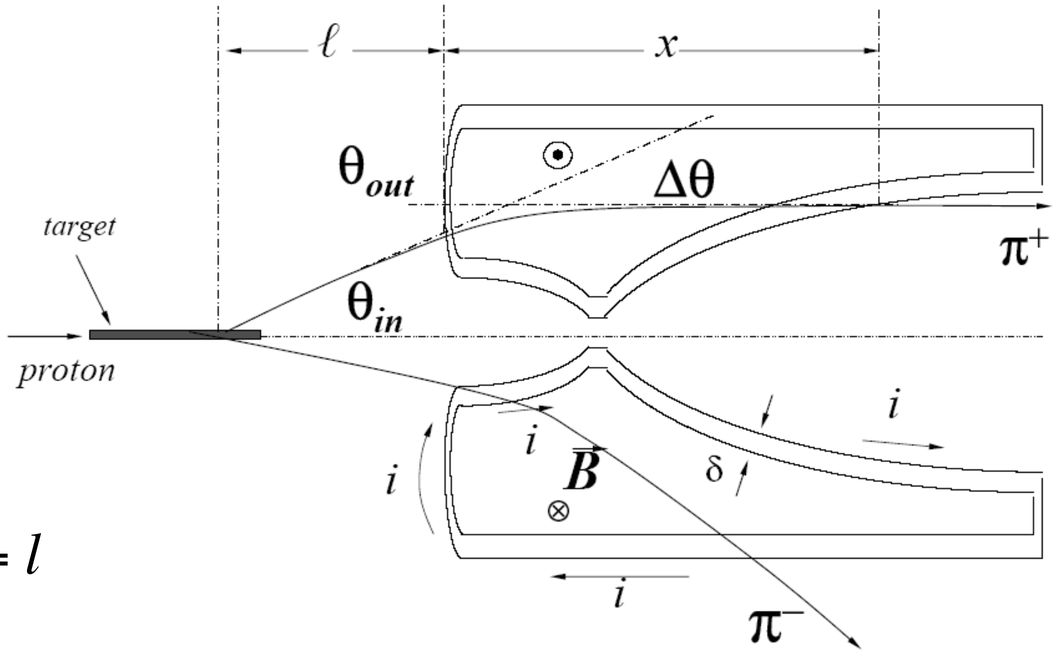
Parabolic Horn

- Parabolic horn developed by Budker for e^+e^- machine at Novosibirsk, adapted to Serpukhov neutrino beam 1967:
  - Focuses a given momentum at all possible angles

$$z = ar^2 \Rightarrow x = 2ar^2$$

$$\Delta\theta = \frac{Bx}{p} = \frac{\mu_0 I}{2\pi r}\frac{x}{p}$$

$$\Delta\theta = \theta_{out} - \theta_{in} = \theta_{out} - r/l$$



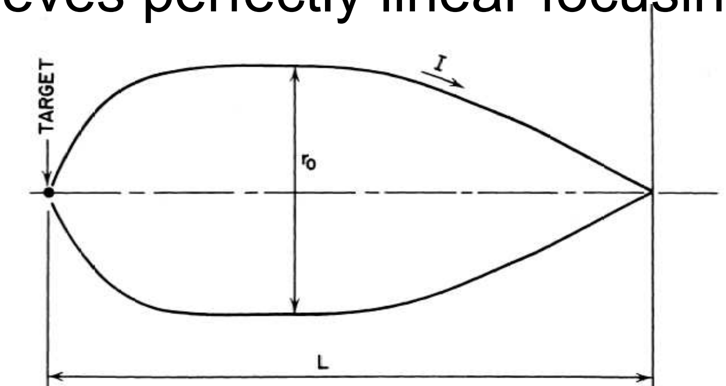
Choose focal point: $f = l$

$$\theta_{out} = 0 \Rightarrow f = \frac{\pi}{\mu_0 a I} p$$

  - Focuses all angles, but focal length depends on momentum

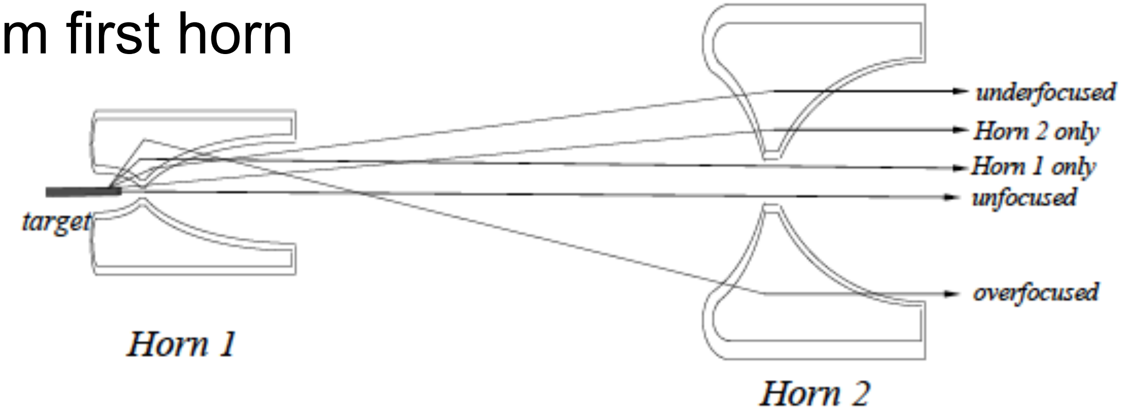
Other Horns

- More sophisticated horns have been designed
  - Ellipsoid horn: similar to parabolic horn but achieves an exact momentum focus across wider angular range (no aberrations)
  - Magnetic fingers (Palmer): adopted at BNL, KEK, MiniBooNE and JPARC: achieves perfectly linear focusing without approximations



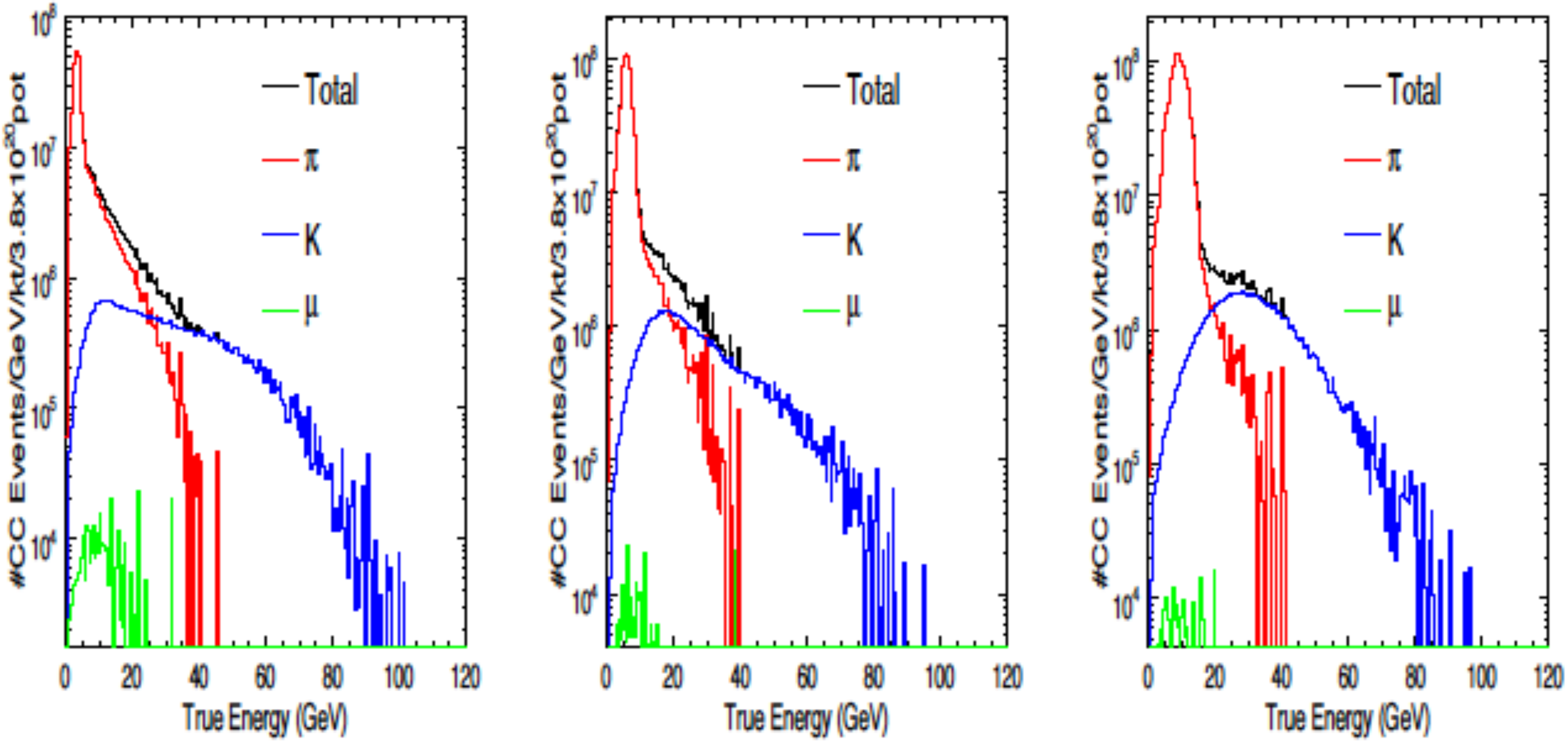
  - Multi-horn systems (Palmer): a second horn can half any residual divergence from first horn

Most facilities now have two horn systems:



Focusing in NuMI Beam

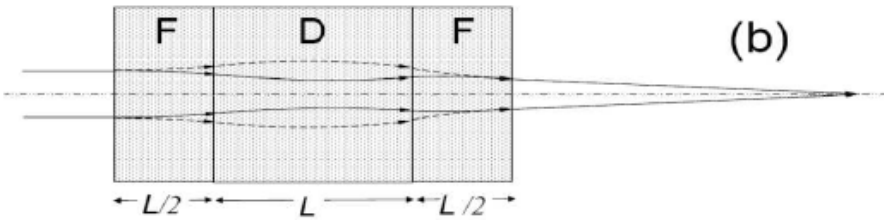
- Effect of focusing at NuMI Beam at FNAL:
  - Three tunes: low, medium and high energy beam

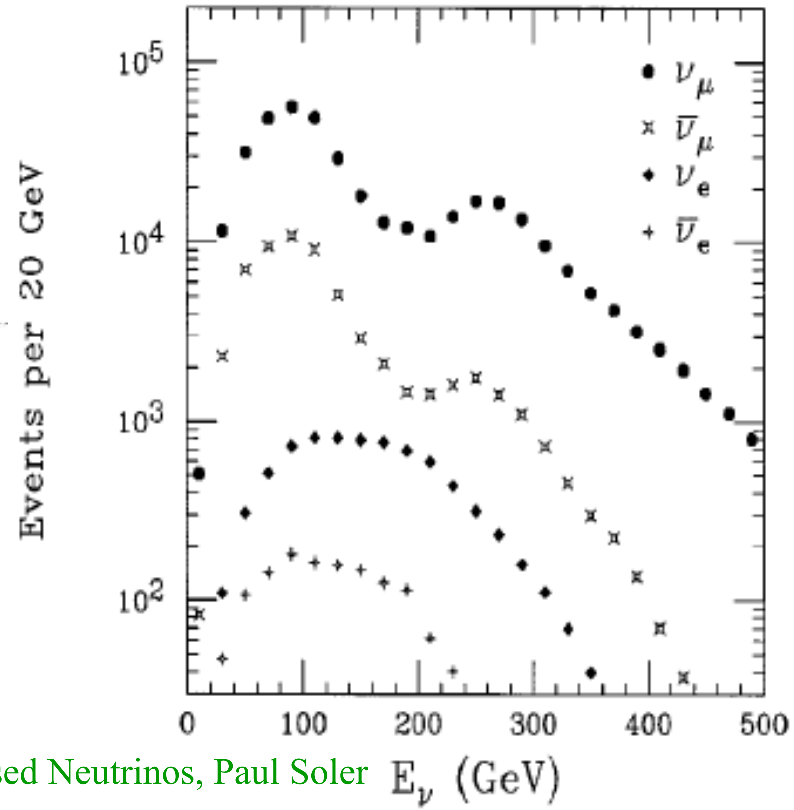


Quadrupole focused beams

- Quadrupole focused beams are less efficient but are useful at high energies since aperture smaller
  - Quadrupole triplet: focuses one momentum at a given distance
  - Only suitable for short baseline: wide band and double peak structure due to under focusing and over focusing of π and K

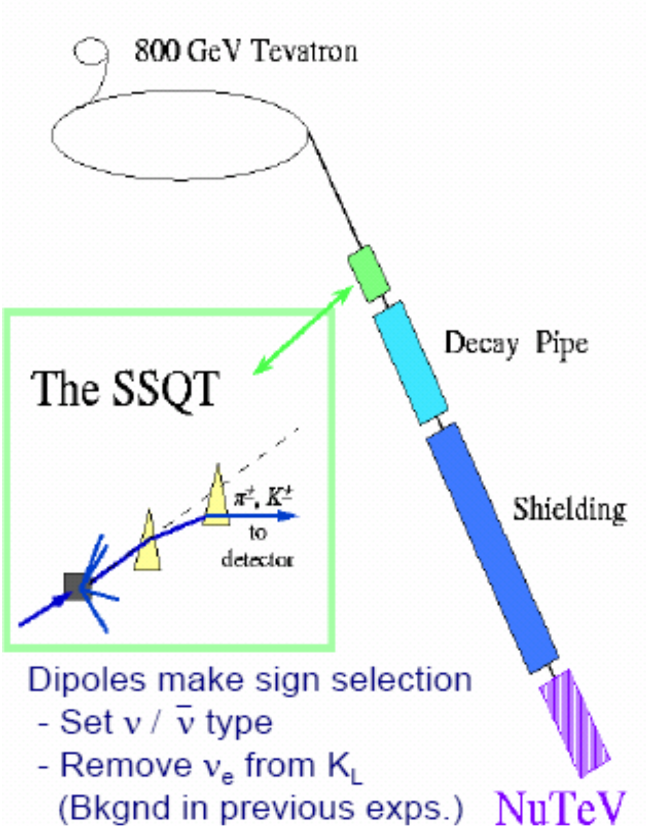
Quadrupoles focus both signs

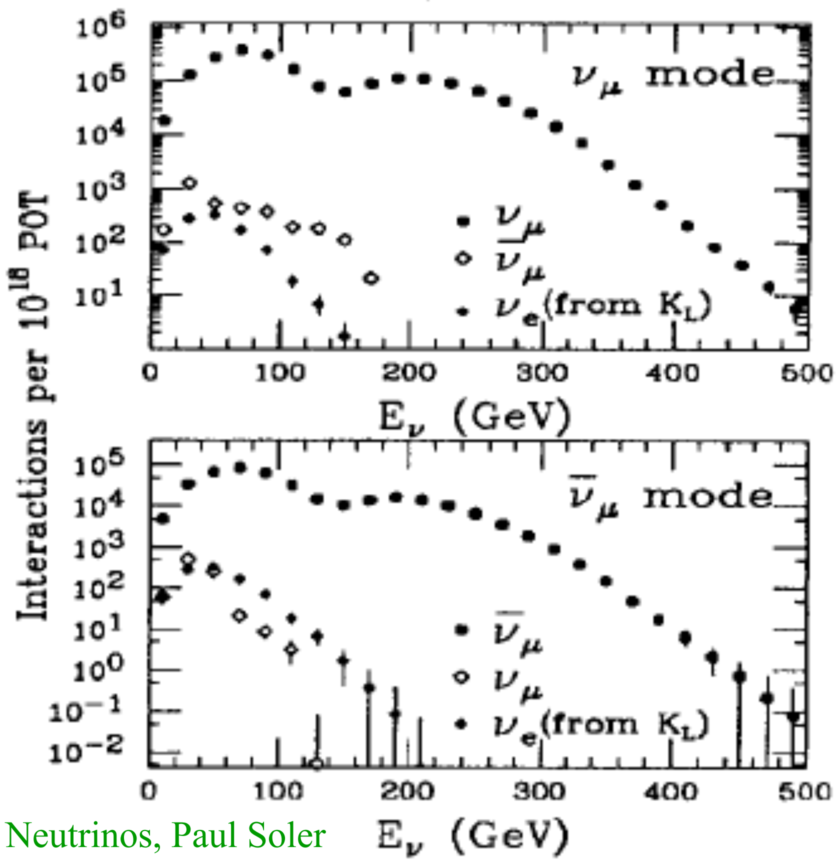




Quadrupole focused beams

- Quadrupole focused beams are less efficient but are useful at high energies since aperture smaller
  - Sign-selected quadrupole triplet: used for NuTeV experiment
  - Add dipole to select only one of the signs of the beam

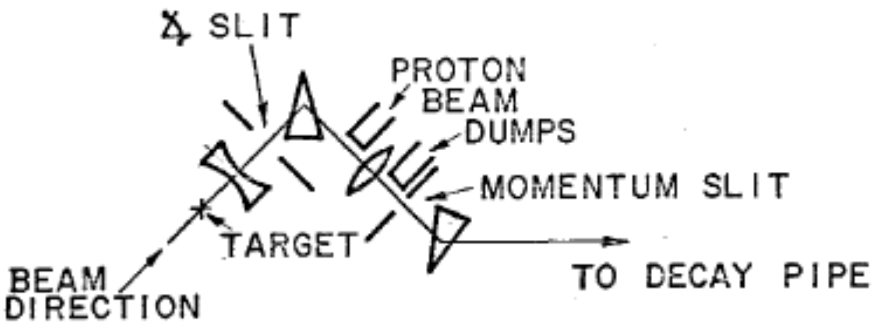


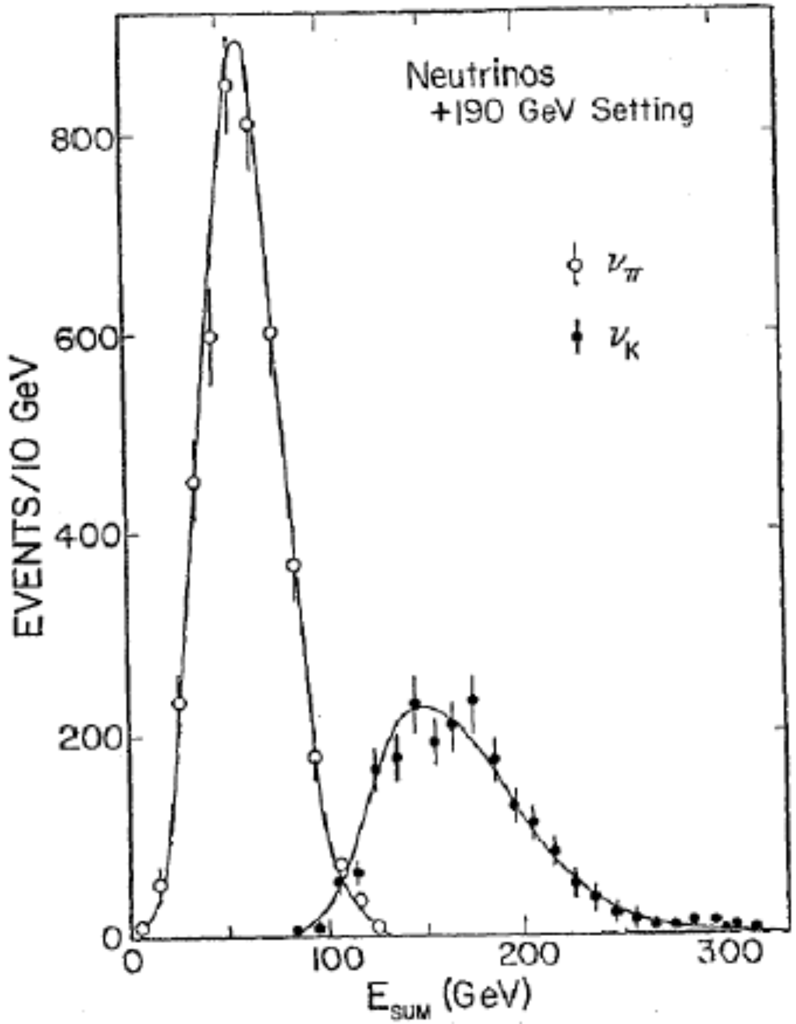


Narrow band beams

- Di-chromatic neutrino beam
  - Dipoles after target sweep wrong-sign secondaries and two quarupoles focus beam

$$E_\nu = \frac{\left(1-(m_\mu/m_{\pi,K})^2\right)}{\left(1+\gamma^2\theta^2\right)} E_{\pi,K}$$

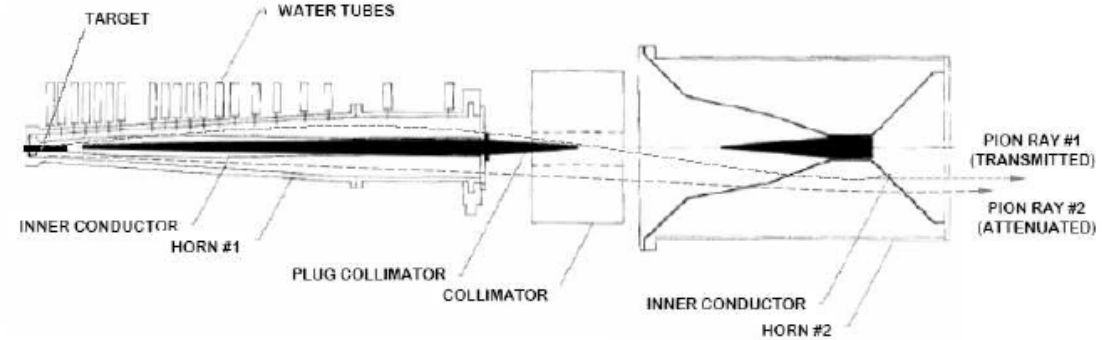




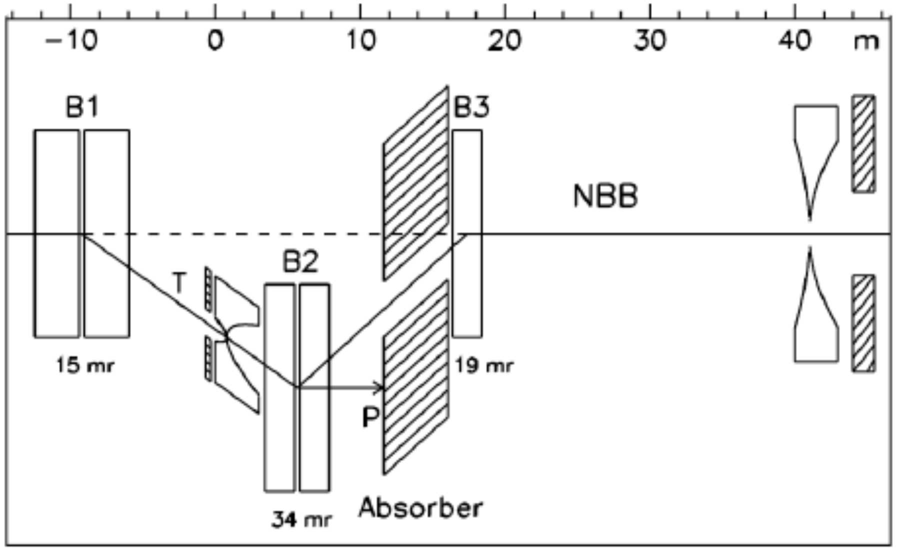
  - Pioneered at FNAL but then used by CERN for CDHS and CHARM experiments at SPS

Narrow band beams

- Horn beam with plug
  - Beam plugs stop unwanted pion trajectories



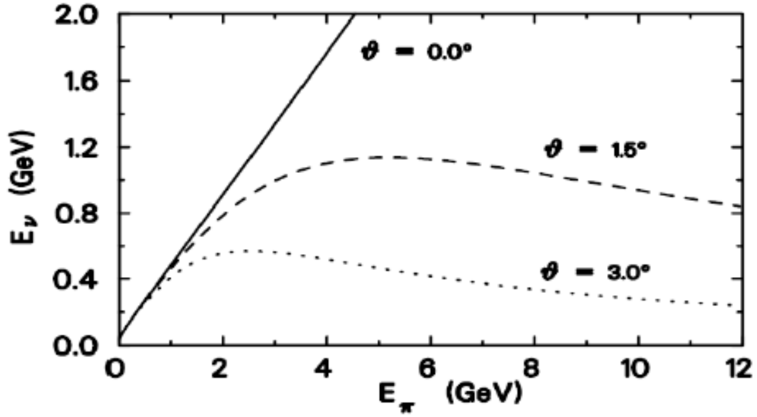
- Horn beam with dipole
  - Dipole between two horns has better momentum and sign selection

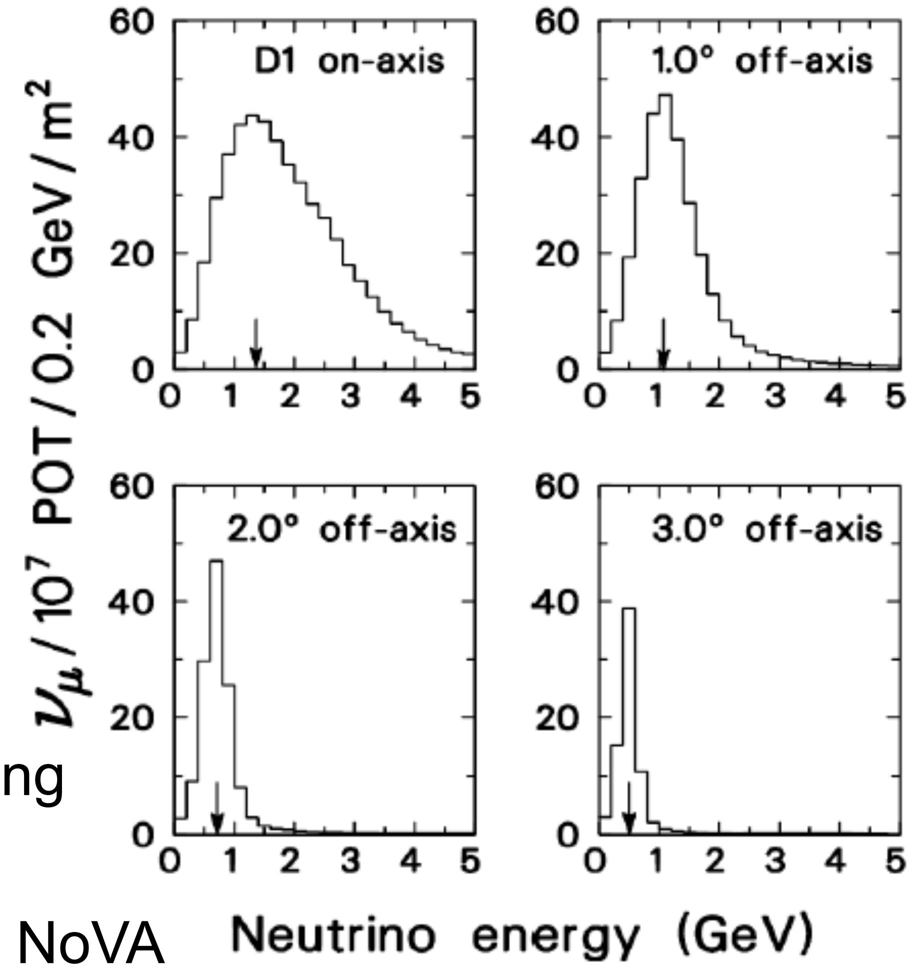


Narrow band beams

- Off-axis beam
  - At θ=0° neutrino energy linear with pion energy, but at off-axis angle, energy narrows

$$E_\nu = \frac{\left(1-(m_\mu/m_{\pi,K})^2\right)}{\left(1+\gamma^2\theta^2\right)} E_{\pi,K}$$





  - Can select energy by choosing off-axis angle
  - Now being used by T2K and NoVA

2. History of accelerator-based neutrino experiments

Part 2

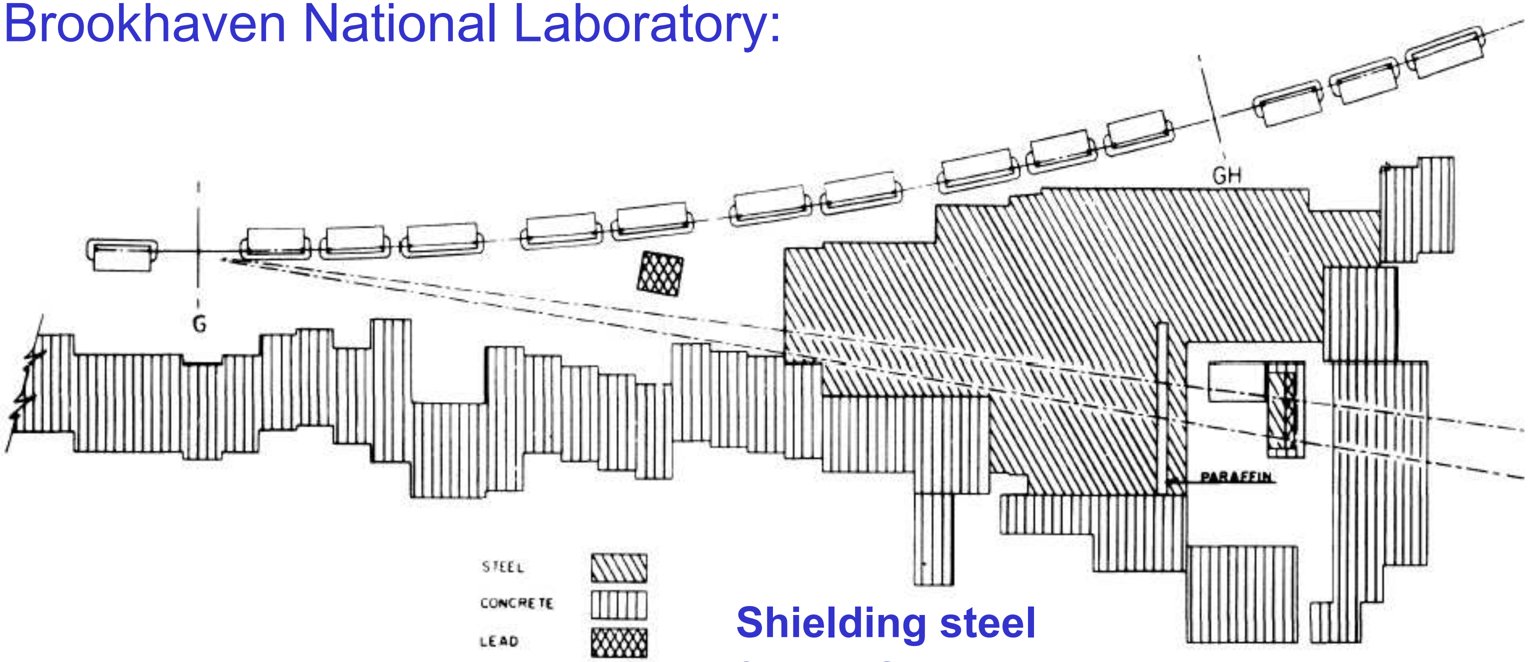
2. History of accelerator-based neutrino experiments
    2.1 The two neutrino experiment
    2.2 Discovery of neutral currents
    2.3 Neutrino interaction experiments, nuclear structure, charm production
    2.4 Discovery of the tau neutrino

The two neutrino experiment

- It was thought that ν_μ and ν_e must be different since certain reactions not observed: conservation of lepton number (for each family).

$$\mu^+ \to e^+ + \gamma \qquad \mu^+ \to e^+ + e^+ + e^- \qquad \mu^+ + N \to e^+ + N$$

- Search for "second" (muon) neutrino carried out in 1962 by Schwartz, Lederman, Steinberger et al. at Alternating Gradient Storage ring (AGS) at Brookhaven National Laboratory:



Shielding steel
from US WWII battleship

The two neutrino experiment

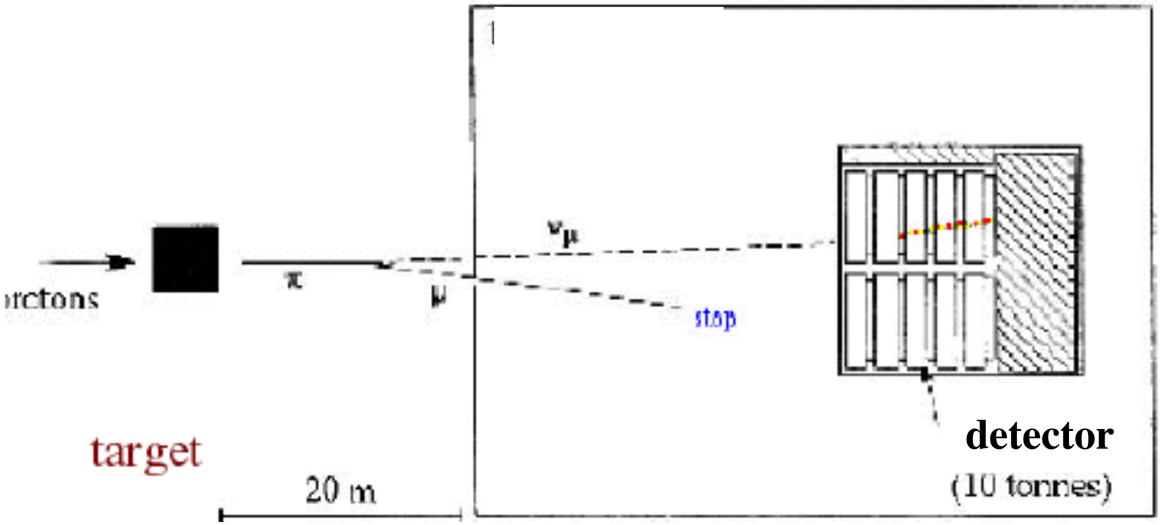
- Used spark chambers to observe muons
- Exposure of 3.48×10^{17} POT: **Discovery muon neutrino**
  - 113 events observed: 56 single muon and vertex events consistent with muons, 49 short events and 8 showers

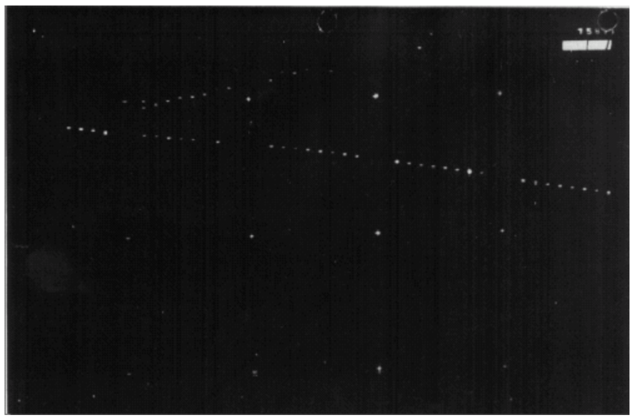
Schwartz, Lederman, Steinberger et al.PRL 9, 36 (1962)

$$\pi^+ \to \mu^+ + \nu_\mu \qquad \pi^- \to \mu^- + \bar{\nu}_\mu$$

$$\nu_\mu + n \to \mu^- + p \quad ALLOWED \qquad \bar{\nu}_\mu + p \to \mu^+ + n \quad ALLOWED$$

$$\nu_\mu + n \to e^- + p \quad FORBIDDEN \qquad \bar{\nu}_\mu + p \to e^+ + n \quad FORBIDDEN$$





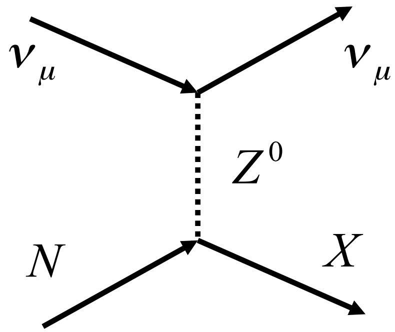
Experimental signature

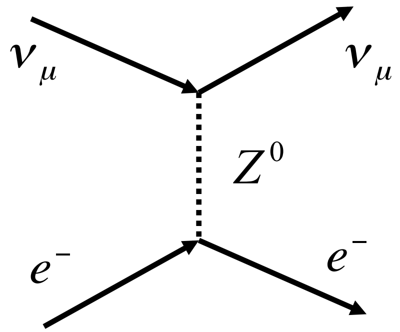
Neutral currents

- Until 1973, the neutral currents (NC) predicted by the electroweak theory of Glashow, Weinberg and Salam had remained elusive
- The neutrino beam came from the CERN PS
- The Gargamelle bubble chamber was 4.8 m long and 2 m in diameter, weighed 1000 tons and had 12 m^3 of freon (CF_3Br)

Neutral currents

- First example of NC observed in 1973, inside the Gargamelle bubble chamber filled with freon (CF_3Br): no muons!
- Gargamelle observed both:
  - Hadronic neutral current
  - Neutral current scattering off an electron





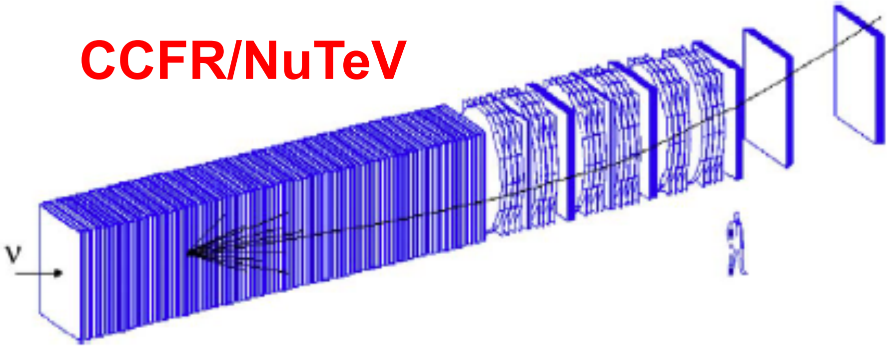
$\nu_\mu + N \rightarrow \nu_\mu + X$ $\quad$ $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$

Phys. Lett. 46, 121 (1973) **Phys. Lett. 46, 138 (1973)**

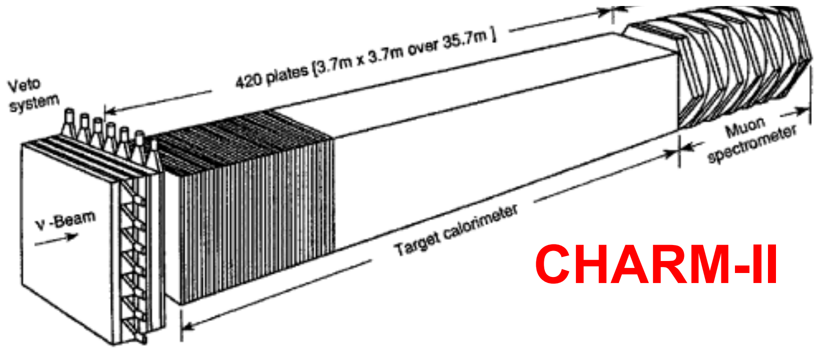
Neutrino experiments in 70s to 90s

- Neutrino experiments at accelerators in the 70s to 90s were mainly dedicated to the study of neutrino interactions, nuclear structure and charm production
  - Bubble chambers: Gargamelle, BEBC and 15 foot chamber
  - Emulsion experiments: ie. E531
  - Calorimetric experiments: HPWF, CDHS, CHARM, CHARM-II, CCFR and NuTeV

CCFR/NuTeV



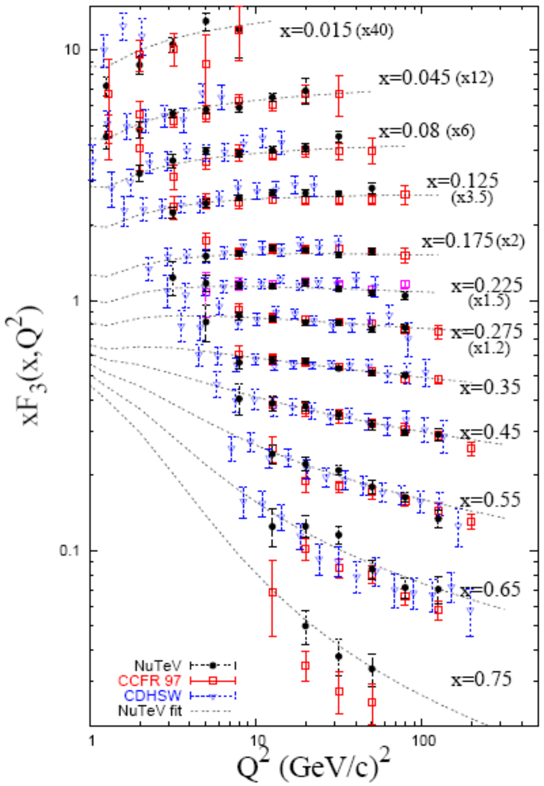
BEBC

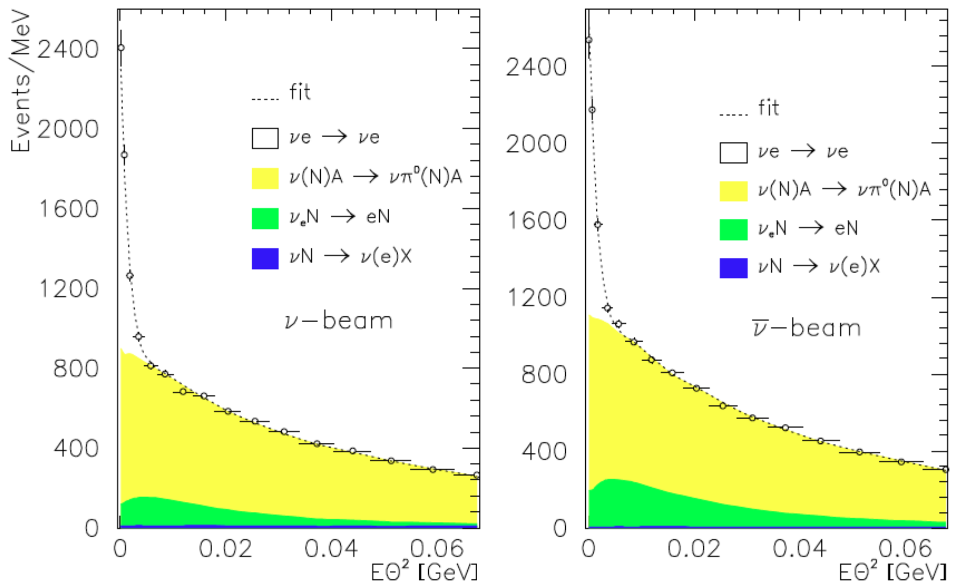


CHARM-II

Neutrino experiments in 70s to 90s

- Some highlights:
  - Structure functions, including unique for neutrino experiments: xF_3
  - Standard model interactions, ie. $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$
  - Standard model parameters: $\sin^2\theta_W$ …..

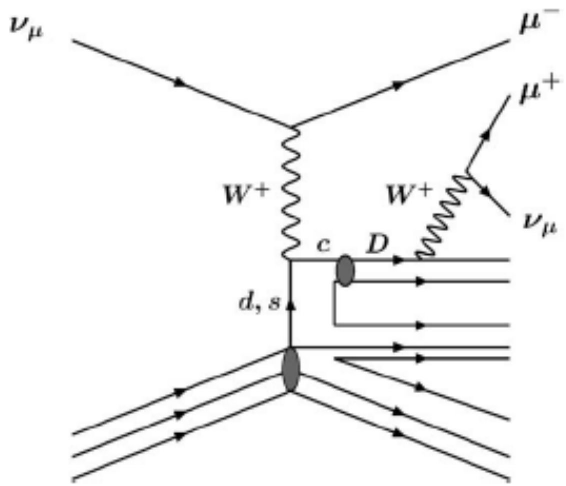


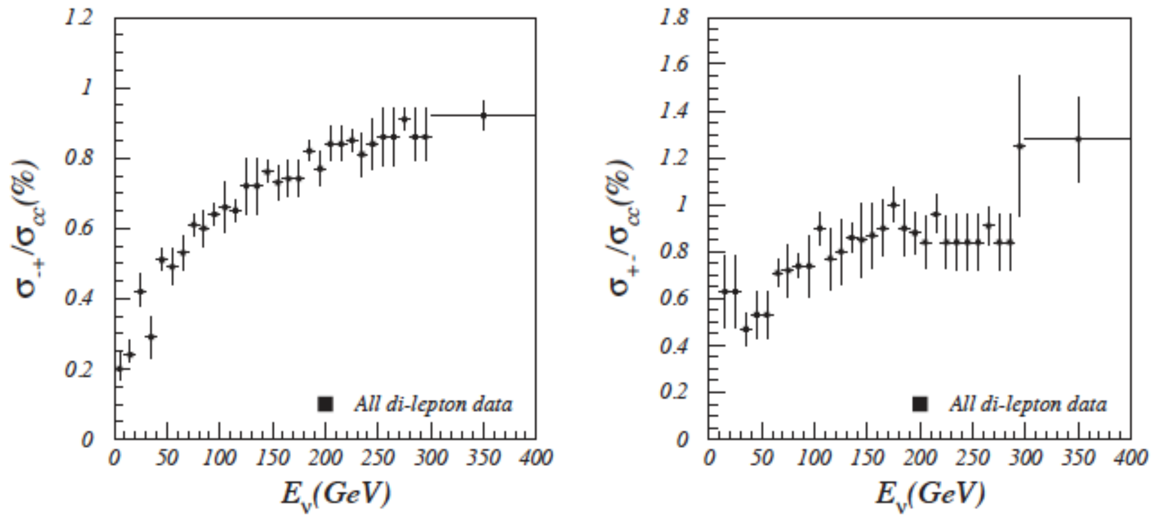


Neutrino experiments played a crucial role in establishing the Standard Model

Neutrino experiments in 70s to 90s

- Also, charm production from neutrino interactions:
  - First evidence of charm particles in HPWF: **Phys. Rev. Lett. 34 (1975) 419**
  - Opposite sign dimuon production is evidence of charm production, and probes strange sea content of nucleons, charm quark mass and V_{cd}





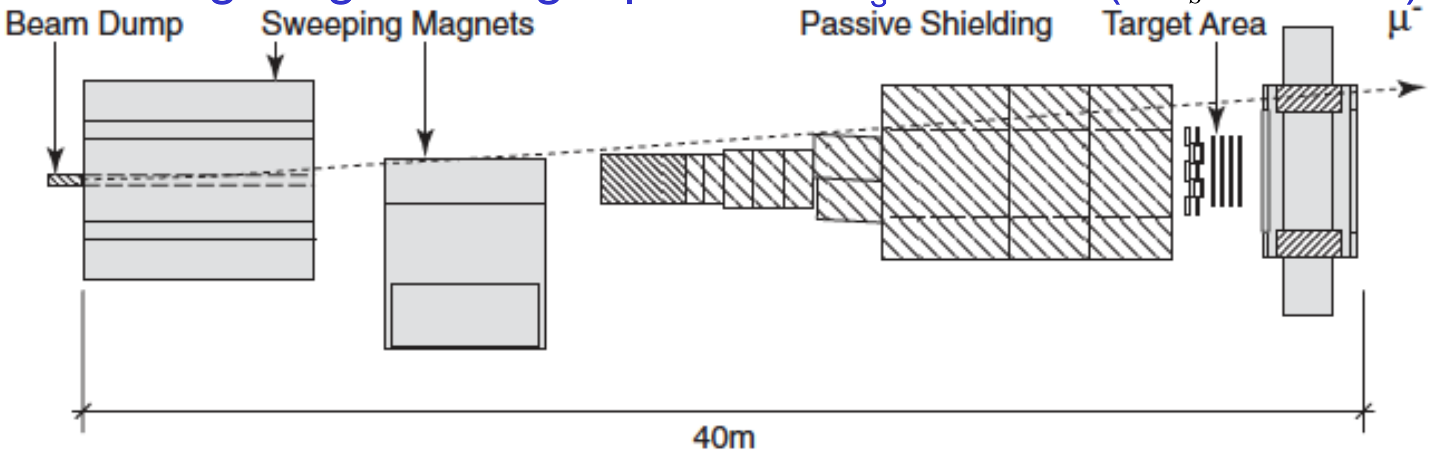
Phys. Rept. 399 (2004) 227

  - Emulsion detectors can distinguish amongst charm states: can determine charm production fractions

    D^0 (0.59±0.06), D^+ (0.14±0.04), D_s^+ (0.11±0.04), Λ_c^+ (0.15±0.04)

Tau neutrino

- First direct evidence for tau neutrino ν_τ in year 2000 by DONUT collaboration at Fermilab:
- Protons hitting tungsten target produce D_s mesons ($D_s^+ = c\bar{s}$).

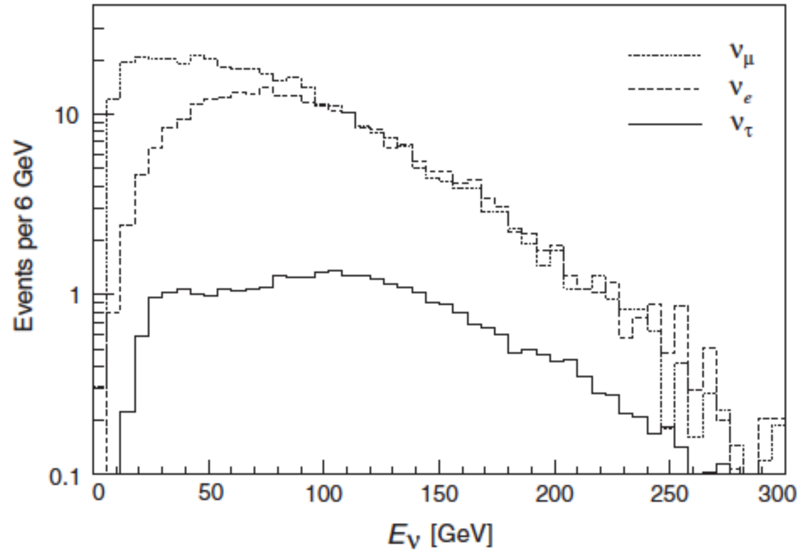


$$D_s^+ \to \tau^+ + \nu_\tau$$

$$\nu_\tau + N \to \tau^- + X$$

$$\tau^- \to \mu^- + \nu_\tau + \bar{\nu}_\mu$$

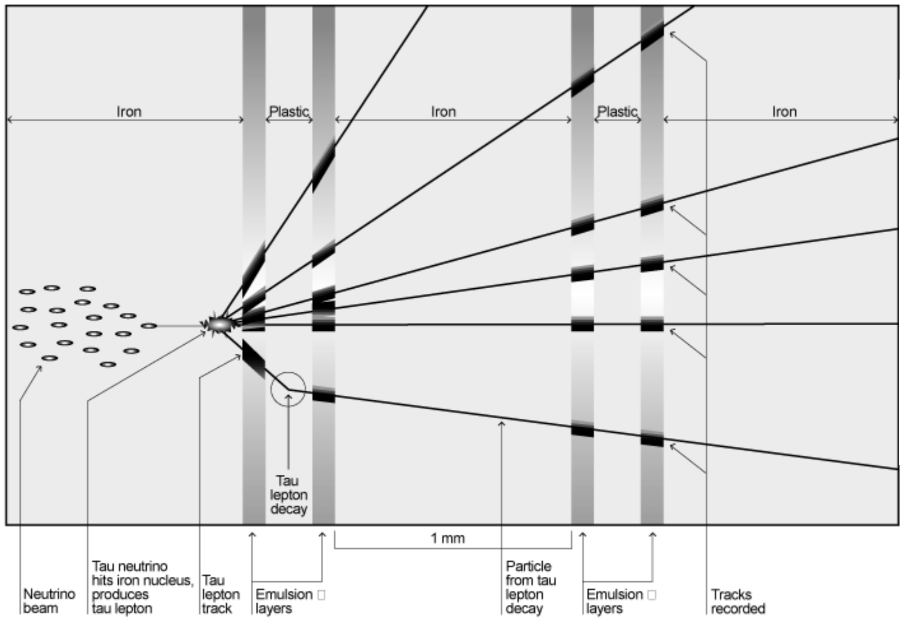
Phys. Rev. D 78, 052002 (20



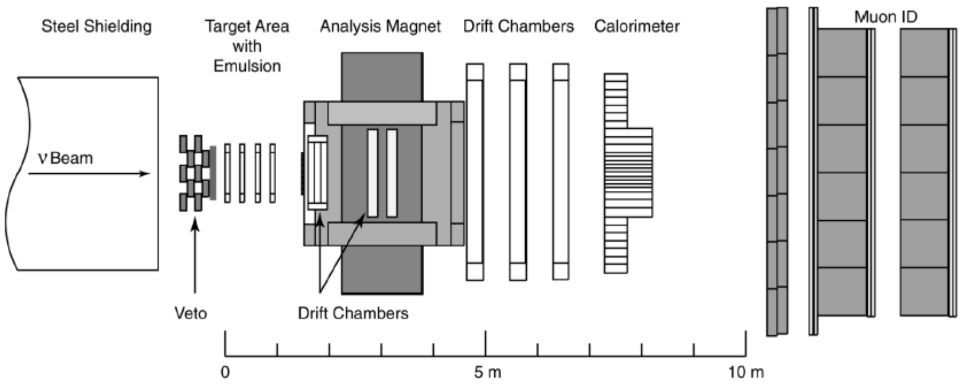
Tau neutrino

- Detection of tau neutrino in emulsion targets. Triggered by spectrometer: 1 mm long track ending in a kink

Detecting a Tau Neutrino



Of one million million tau neutrinos crossing the DONUT detector, scientists expect about one to interact with an iron nucleus.



Phys. Rev. D 78, 052002 (2008)

- Total of 866 neutrino candidate events in the emulsion
- After analysis: 9 events ($7.5\,\nu_\tau$, 1.26 charm, 0.22 hadronic)
- Extracted cross-section: $\sigma^{const}(\nu_\tau) = (0.39 \pm 0.13 \pm 0.13) \times 10^{-38}\ cm^2\, GeV^{-1}$

Compatible with lepton universality

Tau neutrino

- First tau event: